Chapter

Implications of Soil Properties on Landslide Occurrence in Kigezi Highlands of South Western Uganda

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Abstract

Generally, soil characteristics have a significant influence on landslide occurrence. This issue has, however, not yet been adequately analysed in Kigezi highlands of South Western Uganda. In this study, soil properties such as dispersion, grain size distribution, Atterberg limits, shear strength and clay mineralogy were analysed to establish their contribution to the spatial distribution of landslides in Kigezi highlands. The results demonstrate that deep soil profiles ranging between 2.5 and 7 meters were dominated by clay-pans at a depth between 0.75 and 3 meters. Although the uppermost surface horizons of the soil profile are loamy sand, the clay content is more than 35% especially in the sub soil. This suggests that the soil materials are Vertic in nature. In addition, the upper soil layers predominantly contain quartz, while subsurface horizons have considerable amounts of illite as the dominant clay minerals, ranging from 43–47%. The average liquid limit and plasticity index was 58.43% and 33.3% respectively. Besides, high average computed weighted plasticity index (28.4%) and expansiveness (38.6%) were obtained. These soil characteristics have great implication on the timing and nature of landslide processes in the study area. A change in soil material due to varying moisture content is thought to be a major trigger of landslides in Kigezi highlands of South Western Uganda. This understanding of soil characteristics is a key step in mitigating landslide hazards in the area.

Keywords: soil properties, landslide occurrence, Kigezi highlands

1. Introduction

Landslides are among the major life threatening global natural disasters that cause great environmental and developmental challenges [1]. Landslides normally occur on terrains with steep slopes [1, 2]. Slope failures are attributed to factors like topography, geotechnical properties of the material as well as the existence of discontinuities [3, 4]. Most of these factors are specific to particular areas and thus, site-specific studies are important [2]. In Ref. [5] noted that soil types and soil

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texture are primary-level factors, while elevation, land cover types, and drainage density are next in terms of landslide inducement. In [6] the low permeability of fine textured clayey soils exacerbates the vulnerability to landslides. This is due to increased saturation and pore water pressure which reduces soil shear strength [1]. In [7] it is also noted that landslide occurrence is common in regions where sandy clay loams are underlain by sandy clay soils. The stability of slope materials is also influenced by the presence of swelling clay minerals [8]. Soils with high clay content are considered to be the leading cause of landslides in most East African highlands [7]. Soil materials with clay content exceeding 30% and classified as vertic soils, have swell-shrink characteristics [9] which make them highly vulnerable to landslides [10].

In Ref. [11] it is indicated that clay mineralogy affects the shear and frictional resistance of the soils. Among the clay minerals, smectite, particularly montmorillonite, and illite decrease the soil residual strength, owing to their peculiar colloid-chemical characteristic [12] and contribute to landslide occurrence [7]. Montmorillonite a swelling clay mineral, has a negative behaviour, very strong attraction for water and can induce soil collapse due to susceptibility to volume change [13]. The dispersive, collapsible and expansive nature of clay soils constitutes what is referred as problem soils [14]. In [15] it is noted that problem soils are widespread around the world, notwithstanding the little attention they receive in many landslide studies. At various moisture contents, landslides may be induced by problem soils due to their distinct shrink-swell properties [14].

The stability of any slope is affected by specific soil parameters including bulk density, shear strength, clay mineralogy and particle size distribution [1, 7, 16]. Such soil properties vary significantly in space and require site-specific investigations to understand their contribution to landslide occurrence [1, 17]. Whereas previous landslide studies have focused on volcanic soils of Mount Elgon region in Eastern Uganda [1, 7, 18, 19], the present study examines the influence of selected morphological properties of non-volcanic soils on landslide occurrence in Kigezi highlands. The study results provide a comparative analysis of the correlation between soil properties and landslide occurrence in both mountainous as well as highland areas of Uganda.

2. Materials and methods

2.1 Study area

The study was carried out in Rukiga uplands located within Kigezi highlands of South Western Uganda. The study area is situated between 01°21′25″ and 0°58′08″ South, and 29°43′30″ and 30°05′51″ East (**Figure 1**). Rukiga uplands an area covering 427 km^2 [20], span the attitudinally heterogeneous landscapes of Rwamucucu, Maziba, Kashambya, Bubaare, Bukinda, Kamwezi and Kaharo [21] was selected for this study on the basis of its unique topography which is synonymous with reported high incidences of landslides, with visible scars unlike other parts of the highlands where landslide scars have been concealed owing to rapid regeneration [22]. The topography is very rugged, with narrow steep convex slopes and high valleys between hills. Most of these valleys have drainage lines connecting to the main valley [23]. The topography has substantial flat-topped ridges and hills, with short, steep-sided deep valleys fragmented by fluted spurs [24]. Landslide scars were, therefore, identified following an inventory with the help of local communities (**Figure 2**). The landslide scar zones provided soil sampling sites for analysis of soil characteristics and their influence on landslides (**Figure 3**).

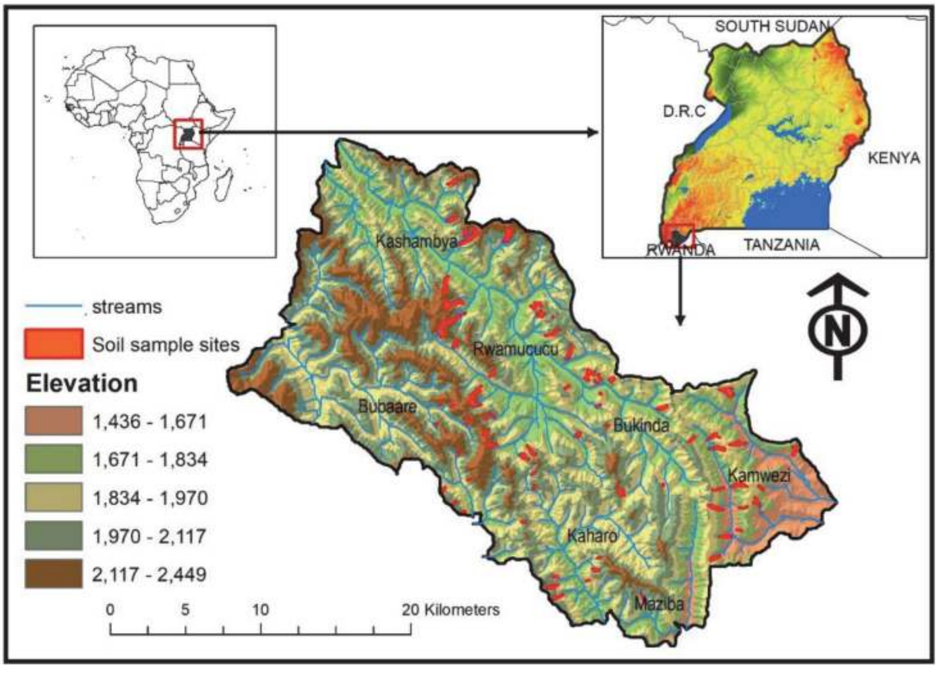

Figure 1.
Location of the study area and soil sampling sites.

Figure 2.
Field investigations to identify landslide scars and soil sampling. Photo credit, Nseka. November, 2019.

The highland's geology is sedimentary in nature of the Precambrian rock system [25], categorised by [26], as phyllite, shale, sandstone, quartzite, granite and gneisses of granitic composition. Other rock types of the study area include grades of schists like quartz-schists and fine textured mica-schists which belong to both the Ankole-Karagwe rock system as well as the Achaean basement complex [25].

Since rock types have influence on slope factors like slope angle and stability, slopes with phyllites and shales underneath are more affected by instability processes compared to those covered by quartzite and micaceous sandstones [25]. Additionally, slope sections with relatively weaker rocks beneath like shales have deep soil profiles attributed to high weathering rates [23]. Besides, slopes underlain

Figure 3.
In-situ soil property analysis within the landslide scars. Photo credit, Nseka. November, 2019.

by quartzite and granitic intrusions are less prone to landslides because they are covered by shallow soils and in some cases by bare rocks [25]. Most of the water courses within the highlands contain varied patches of alluvia sand and clay [26]. For example, coarse sands have been oberved in the warped valleys with gneiss and granite intrusions beneath, while shale and phyllite are associated with clay deposits [25]. By implication, the local geology has an important influence on landslide occurrence in the highlands. The soil types in the study area include Luvisols, Histosols, Acric Ferralsols and Dystric Regosols [23].

The climate of Kigezi highlands is warm to cool humid, characterised by a bimodal rainfall pattern with annual rainfall of 1092 mm [20] classified as moderate. Rainfall, however, increases from 1250 to 1540 mm or more in high altitude areas of greater than 2000 m above sea level [27, 28]. The main rainfall seasons span from mid-February to May with a peak in March/April, and September to December with a peak in October/November [29]. Since the highland receives significant amounts of rainfall, the study area has various highlands streams which drain valleys incised within the ridges and hills [30]. Until about a century ago, the highlands' vegetation cover was characterised by montane forests [23]. Depletion of vegetation cover has occurred in the highlands due to increased human interference [31]. The highlands of the study area are currently characterised by *Eucalyptus globulus*, *Pinus leiophylla* and farmlands [28].

2.2 Soil morphological analysis

To evaluate the soil morphology-landslide relationships, field investigations were conducted and soil samples taken at different depths and points along the slope profile and positions. In this study, 120 soil samples were collected and used in the analysis of soil morphological characteristics. Soil description was done according to FAO guidelines [32]. Visible landslide scars were identified and categorised into 10 groups based on their morphological characteristics.

Profiles in the upper slope sections were dug to a depth of 1 to 1.5 m (classified as shallow). Profiles in the middle slopes ranged between 2 to 4 m (medium) while those in the lower sections were greater than 5 m (deep). Soil samples were obtained from within and outside the landside scars. Onsite analysis of physical soil properties was conducted within landslide scars, min pits, auger holes, and full profile representative sites (**Figure 3**). Site analysis sought to characterise among other things, soil matrices and bedrock within each landslide. Soil horizons were analysed in detail with a specific focus on depth, colour, texture, presence and location of claypans, and structure.

2.2.1 Soil-water infiltration

Characterisation of soil infiltration levels is an importance aspect when analysing any landslide occurrence in a given region [26]. Quantification of infiltration rates is important to understand the mechanism of slope failure [25]. In situ infiltration tests were performed purposely to measure soil-water infiltration rates. Infiltration tests were performed at various slope positions including lower-bottom, lower-middle, upper-middle and uppermost. This was done owing to variations between topographic configurations and soil characteristics. A total of 32 experiments were performed on 4 landslide sites with different land use and cover categories. Field measurements of soil-water infiltration were done using the double ring infiltrometer method [33] consisting of two concentric metal rings [34, 35].

2.2.2 Rainfall data

The frequent heavy rainfall received within Kigezi highlands have been observed to be a main trigger of landslides because, the rains increase pore water pressure in voids [28]. Given the importance of pore water pressure and antecedent moisture in triggering landslides in the study area [23, 29], rainfall data are important in their analysis [24]. The rainfall data used in this study were obtained from Kabale Meteorology Station, weather data 2015: WMO No. 63726, National No. 91290000, station name Kabale, at Elevation 1867 m, Latitude 01°15′, Longitude 29° 59″. Rainfall data were compared with landslide occurrence periods to ascertain their relationships.

2.3 Laboratory analyses

The scope of laboratory testing comprised shear box, Atterberg limits, sieve and hydrometer analysis, specific gravity using test standards and XRD analysis. For purposes of defining the dominant soil mechanical and physical properties, several laboratory tests were undertaken. The grain size distribution, unit weight, natural water content, degree of saturation and Atterberg limits were among the major physical and mechanical soil properties examined. Soil property tests were undertaken in accordance with the British Standard BS 1377 procedures [36]. These tests were used in the estimation of porosity, dispersion, saturated specific weight, and saturation humidity. These soil properties were considered relevant in understanding and characterising site-specific landslide controls ("For example, see [1, 7, 17]").

2.3.1 Determination of particle size

Particle size was determined using mechanical analysis. In this method, the size range of particles within a soil sample was determined and the results were expressed as a percentage of the total dry weight. To determine the soil particle-size distribution, *Sieve analysis* and *Hydrometer analysis* methods were used on particle sizes greater and less than 0.075 mm in diameter respectively. Sieve analysis involved shaking of the soil sample through a set of sieves (ranging from 75.00 mm to 0.075 mm). The percentage of the finest size and that of the weights retained on each of a series of standard sieves of decreasing size were used to infer particle size distribution.

2.3.2 Atterberg limits

A number of soil samples obtained from the landslide sites were used for Atterberg limit tests undertaken in the geotechnical laboratory. The tests were conducted to determine among others the clay plasticity and measure the threshold water contents of a fine soil. Atterberg limits were used to determine soil plasticity which provides a clue to the type of mass movement that would characterise a given area ("For example, see [37]"). The Atterberg limits were important in determining among others, soil strength, type, stability, behaviour, and state of consolidation. Using the procedures in ASTM Standard D 4318 and D431/84 and also CNR UNI 100141 ("For example, see [38]") the limits were determined as Liquid Limit (LL) and Plastic Limit (PL). The tests gave an indication of the levels of saturation and response of a soil material to landslides. The results of grain-size distribution and Atterberg limits tests were used to classify the colluvium soils according to the Unified Soil Classification System which enabled further classification of fine materials.

2.3.3 Soil dispersion tests

A double hydrometer test was used based on Stoke's law of settling velocity as an indicative laboratory test for identification of dispersive soils ("For example, see [11, 14]").

2.3.4 Soil expansiveness

To determine whether the soils in the study area are susceptible to slope failure, investigations were done to determine the expansiveness of the soil. Three procedures were done to determine the expansiveness of the soil in the study area. During such field surveys, a description of the crack patterns on the soil surface was done at different sites to determine the swelling-shrinking characteristics of particularly clay soils. The second procedure entailed calculating the weighted Plasticity Index (PI_w) on the fraction <425 μm and weighted for the sample's actual content of particles <425 μm using the formula:

$$PI_w = PI * (\%\text{passing } 425\mu m)/100. \tag{1}$$

Where PI is the Plasticity index.

The third procedure involved calculating the expansiveness (ε_{ex}) using the formula:

$$\varepsilon_{ex} = 2.4w_p - 3.9w_s + 32.5, \tag{2}$$

Where; w_p = (Plastic Limit) * (%passing 425 mm)/100 and w_s = (Shrinkage Limit) * (%passing 425 mm)/100.

2.3.5 Clay mineralogy analyses

Clay mineralogical composition was analysed using X-ray diffraction. Soil samples were prepared for XRD analysis using the back loading preparation method ("For example, see [39]"). A PANalytical Aeris diffractometer with PIXcel detector in combination with fixed relative phase amounts (weight %) were estimated by X'Pert Highscore plus software and Rietveld method respectively.

2.3.6 Shear strength tests

To determine material strength, shear strength tests were executed on samples obtained from the landslide sites. These tests included Shear Box and Unconsolidated – Undrained (UU) tests. The tests were conducted to determine the shear strength parameters of soil cohesion (c) and the angle of internal friction (ϕ) in accordance to British Standard (BS) 1377: Part 7: 1990 [36].

3. Results

3.1 Soil morphological properties

3.1.1 Soil profile characteristics

At the depth less than 0.85 m, shallow soil groups were observed and these occured on very steep (i.e. between 35° and 45°), and precipitous (i.e. >45°) slopes. Medium and deep soil groups in the range of 1.5–4 m and greater than 6 m, were found occupying midslopes along topographic hollows and lower slopes respectively. Surface layers were covered by deposited black soils with an average depth of 0.5 m to 1 m. The B and C horizons had depths ranging from 0.65 m to 3.44 m and 0.88 m and 5.7 m, with a reddish-brown colour and coarse-textured materials concentrated in the lowest layers, respectively. At a 1.3 m depth along the spur slopes, unweathered materials were observed. Other unweathered materials were observed at a depth of 4.5 m along topographic hollows and 7 m deep in the valley bottoms. Along the soil profiles, visible colours and textural gradation within 3 distinct horizons were seen. An abrupt change in colour from yellow (5Y8/2) to brown (7.5YR5/2) clay with Gs 2.9 g/cm^3 and γ 2.06 g/cm^3 was exhibited in the upper slope elements for most of the analysed profiles. Dark reddish brown (5YR 3/6) and orange (7YR 5/6) colour in moist and dry conditions respectively characterised most of the surface horizons. Surface horizons with brown (7.5YR 4/4) colour in both moist and dry conditions and a dark to dull reddish-brown colour (7.5YR 4/6) in underlying horizons dominated most of lower slope element profiles. Soil colour in combination with other physical properties, were used to differentiate horizon types of the same and different soil profiles.

A relationship was noticed between the regions topographic characteristics and the depth of soil. Basing on the soil profile description, it was noted that the depth of soil reduced with an increase in slope angle. Whereas very deep soils (>5 m) were dominant on slope sections with slope angles less than 10°, moderately deep soils (2 to 5 m) were noticed on slope angles between 15° and 35°. Slope elements with slope angles greater than 35°, were characterised with shallow thin soils of less than 1 m (Appendix 1). A relationship was also established between slope curvature and the depth of the soil. Very deep, deep and moderately deep soil profiles (>2.5 m) were dominant along concave profile elements common in topographic hollows. Convex profile elements along spur slopes and hilltops were dominated by shallow thin soils of less than 1 m (Appendix 1).

3.1.2 Location of clay pans

Field observations within dug profiles indicated the presence of claypans at a depth of 0.75 m to 3 m (**Figure 4**). Variations in the location of claypans is noticeable along the soil profile. In some profiles, the claypans were found close to the surface while in some horizons they were identified at greater depths. Whereas the upper slope soil profiles had claypans close to the surface at less than 0.85 m depth,

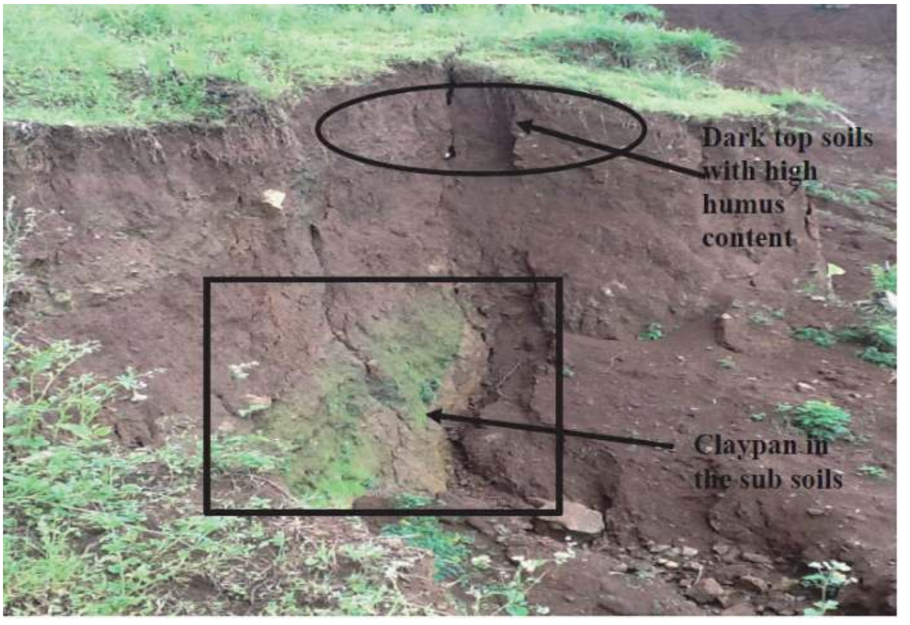

Figure 4.
Soil profiles dominated by claypans in the sub-surface soil horizons. Photo credit, Nseka, may 2019.

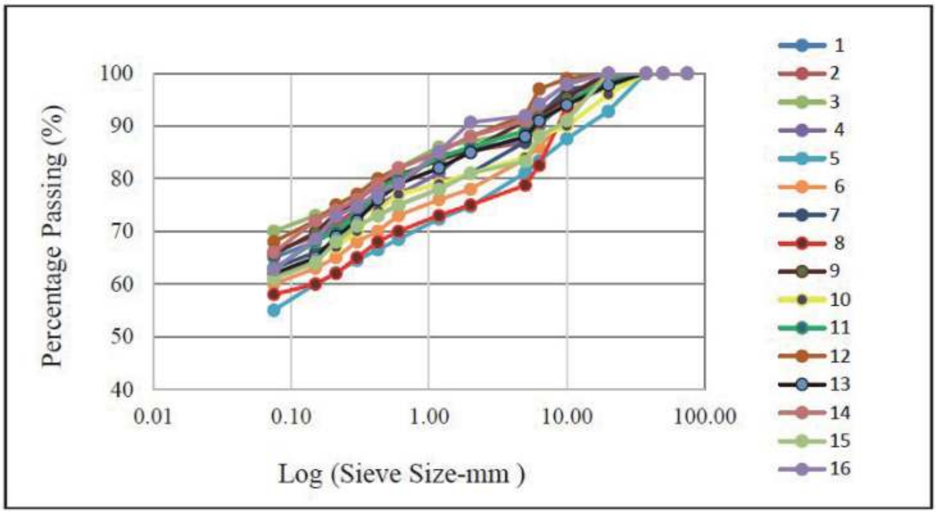

Figure 5.
Particle size distribution curves.

lower slope soil profiles had pans at greater than 2 m depth. Claypans in soil profiles along the middle slope sections existed at depth ranging between 1 and 2 m. Characterising variations in depth of claypans horizon is an important step in explaining other soil properties, as expounded in the discussion section.

3.2 Effect of particle size on landslide occurrence

The study area is dominated by clay soils in the subsurface horizons. The particle size determination (**Figure 5**) shows that soils are dominated by clay presence, except for the uppermost surface horizons.

From the materials analysed, fine grained materials of either clay or silt were predominant (**Figure 5**). The texture of the soil varied with profile depth as revealed by sieve analysis. In the subsurface horizons, finer clay and silt materials dominates, while sand particles are the most dominant in surface soils. It was observed that all surface horizons had sand (33–55%), silt (22–40% and clay (10–30%). In the deeper horizons, sand was observed to reduce drastically to less than 23%, while clay increased to greater than 50% (Appendix 1). The clay content for all the samples in the sub soil and deep soil horizons is well above the 32% threshold for vertic soils. The swelling and shrinkage characteristics of vertic soils are very important in the localisation of landslides, as explored in the subsequent section.

3.3 Clay mineralogy and landslide occurrence

The results of the X-ray diffraction tests are provided in **Figure 6** and **Table 1**.

Following the X-ray diffraction patterns, it was established that quartz, illite/muscovite and kaolinite are the dominant minerals in the soil materials. From the soil mineralogical analysis conducted, it was established that quartz was the dominant soil constituent within the top layers. By implication, these high amounts of quartz within surface soil horizons affect the behaviour of the soil to incoming rainfall as will be unravelled in the subsequent section. Considerable amounts of illite/muscovite as the dominant clay minerals, ranging between 43% and 47% (**Table 1** and **Figure 6**) were present in the subsurface soil horizons. Notwithstanding the absence of smectite clays, the soils contain large amounts of moderately expansive clays, particularly illite/muscovite.

3.4 Soil dispersion and landslide occurrence

The LL and Plasticity Index for all the tested samples are greater than 50% and 30% respectively (**Figure 7** and **Table 2**).

The fine-grained soil materials tested had LL with an average value of 58.43%, ranging between 50.43% and 66.43%, which is considered to be of high plasticity. Whereas the plasticity index ranged between 22.4% and 44.2%, the plastic value ranged between 21.3% and 28.9% (**Figure 7**). High plasticity index of more than 30

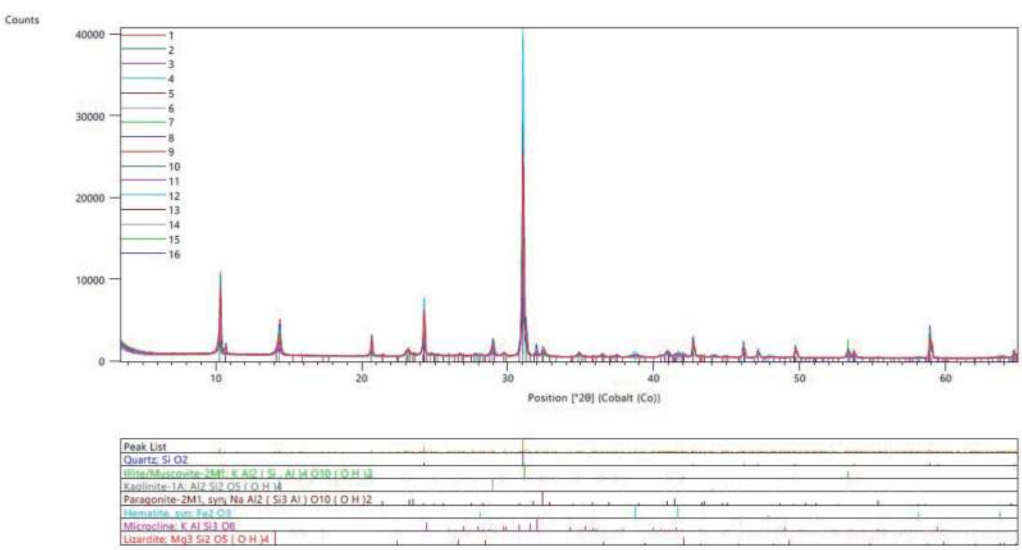

Figure 6.
XRD patterns of clay minerals.

Samples	Soil horizon	Quartz	Illite/ muscovite	Kaolinite	Paragonite	Haematite	Microcline	Lizardite
1	Top soil	56	26	9	4	1	0	4
2	sub soil	46	43	7	2	1	0	1
3	Top soil	60	27	6	6	2	0	0
4	sub soil	39	43	8	4	3	1	1
5	sub soil	42	41	10	3	2	1	1
6	sub soil	43	45	8	2	1	1	0
7	sub soil	43	42	9	3	1	1	0
8	sub soil	36	47	11	3	1	1	1
9	sub soil	36	44	12	5	1	1	1
10	Top soil	75	18	5	0	2	0	0
11	Top soil	62	28	6	2	1	0	2
12	Top soil	76	16	6	1	0	1	0
13	Top soil	71	22	5	0	1	0	2
14	sub soil	41	46	7	4	0	1	1
15	Top soil	64	22	6	4	2	0	2
16	Top soil	82	12	3	2	0	2	0

0 = n.d. – not detected above the detection limit of 0.5–3 weight percent.

Table 1.
XRD mineral distribution in percentages.

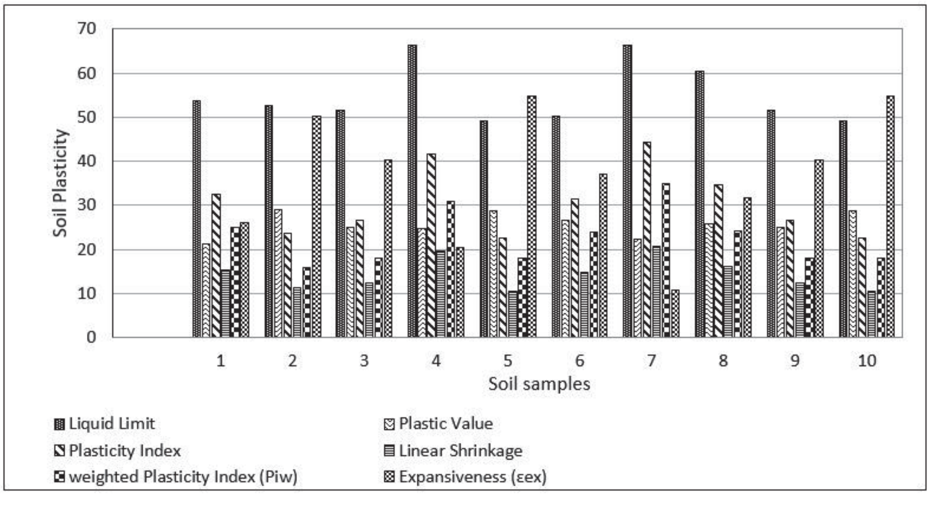

Figure 7.
Plasticity index parameters.

was detected in the clay materials, thus rendering them as highly plastic and expansive. The computed Linear Shrinkage (LS) ranged between 10.53 and 20.76. Whereas soil expansiveness (ε_{ex}) ranged between 10.7 and 54.8 averaging 38.6, the computed weighted Plasticity Index (PI_w) ranged between 17.92% and 34.92% averaging 28.4% from all the analysed soil samples (**Figure 7**). As regards to soil

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Soil sample	Plasticity								Shear strength parameters		Soil class	USCS
									C′	φ′		
	LL	PL	PI	LS	w_p	w_s	PI_w	ε_{ex}	kPa	(Degree)		
1	58	26	31	15	20	11	24	37	7	3	Clayey	CH
2	54	21	32	15	16. 4	12	25	26	7	4	Clayey	CH
3	66	22	44	21	18	16	35	11	5	5	Clayey	CH
4	58	27	31	15	20	11	23	39	7	4	Clayey	CH
5	53	29	24	11	19	8	16	50	9	5	Fat Clay	CH
6	60	26	35	16	18	11	24	32	10	7	Clayey	CH
7	54	27	27	13	20	9	20	45	8	6	Clayey	CH
8	52	25	27	12	17	9	18	40	6	3	Clay Loam	CH
9	56	24	32	15	19	12	26	31	9	3	Clay Loam	CH
10	66	25	42	20	18	15	31	20	10	8	Clay Loam	CH
11	50	23	27	13	18	10	21	37	11	7	Clay Silt	CH
12	49	29	22	11	23	8	18	55	5	4	Clay Silt	CH
13	60	27	33	16	20	12	25	35	7	4	Sand Clay	CH
14	57	23	34	16	19	13	27	28	8	4	Sand Clay	CH
15	57	28	29	14	21	10	21	43	7	3	Clay Loam	CH
16	53	26	28	13	20	10	15	36	8	5	Clay Loam	CH
17	49	24	27	13	18	8	21	41	7	3	Clay Silt	CH
18	50	26	31	15	20	11	24	37	7	4	Silty Clay	CH
19	52	21	32	15	16	12	25	26	5	5	Silty Clay	CH
20	66	22	44	21	18	16	35	11	7	4	Clay Loam	CH
21	58	27	31	15	20	11	23	39	9	5	Sand Clay Loam	CH
22	53	29	24	11	19	8	16	50	10	7	Clay Silt	CH
23	60	26	35	16	18	11	24	32	8	6	Clay Loam	CH
24	54	27	27	13	20	9	20	45	6	3	Sand Clay	CH
25	52	25	27	12	17	9	18	40	7	3	Sandy Loam	CH
26	56	24	32	15	19	12	26	31	7	4	Clayey	CH
27	66	25	42	20	18	15	31	20	5	5	Silty Clay	CH
28	50	23	27	13	18	10	21	37	7	4	Clay Loam	CH
29	49	29	22	11	23	8	18	55	9	5	Clayey	CH
30	60	27	33	16	20	12	25	35	10	7	Silty Clay	CH
31	57	23	34	16	19	13	27	28	8	6	Clay Loam	CH
32	57	28	29	14	21	10	21	43	6	3	Clay Loam	CH
33	53	26	28	13	20	10	21	41	9	4	Sandy Loam	CH
34	49	24	27	13	17	9	20	39	9	6	Clayey	CH

Table 2.
Plasticity index and shear strength parameters.

expansiveness (ε_{ex}), all the tested samples were in the range between 20 and 50, and this indicated medium expansive soils which were susceptible to landslides.

From the plasticity chart (**Figure 8**), all the soil samples tested were inorganic clay of high plasticity belonging to the CH group. Such soils can easily move when saturated, leading to a high incidence of landslides.

From **Figure 8**, it is evident that soils in the study area have high plasticity as already revealed by XRD results. Such soils can easily move when saturated, leading to high incidence of landslide occurrence. The presence of many cracks, observed on the soil surface during field investigations confirms the high plasticity nature of the soil materials (**Figure 9**). The presence of such cracks on the surface is also a characteristic of Vertisols with high expansive potential.

From the double hydrometer test, it can be vividly observed that most of the samples have dispersion values greater than 30%. By implication, such soil materials are susceptible to landslide occurrence. From the soil samples examined, critical dispersion values greater than 50% were established from more than 90% of the samples (**Figure 10**). Such high dispersion values imply greater susceptibility to landslides in the region. This study established that, highly dispersive soils are particularly dominant in the surface soil layers associated with greater percentages of illite/muscovite clay minerals.

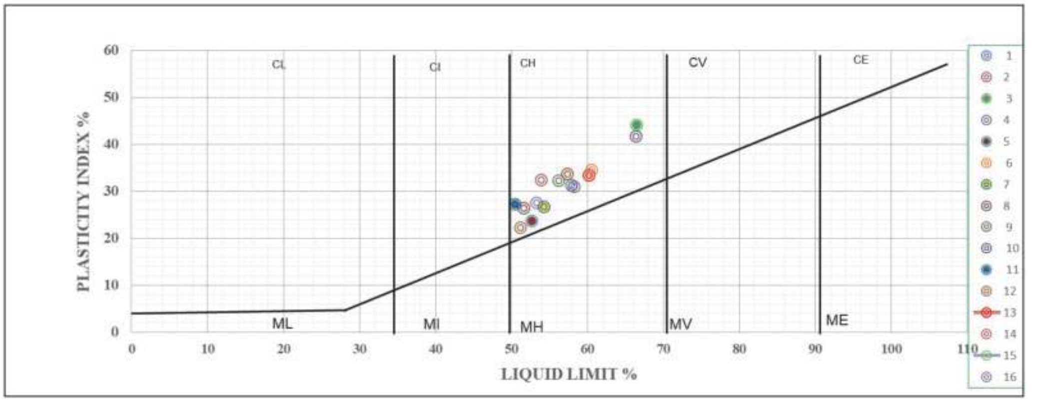

Figure 8.
The distribution of samples on the plasticity chart for the USCS.

Figure 9.
Highly expansive materials with numerous surface cracks. Photo credit, Nseka, march 2019.

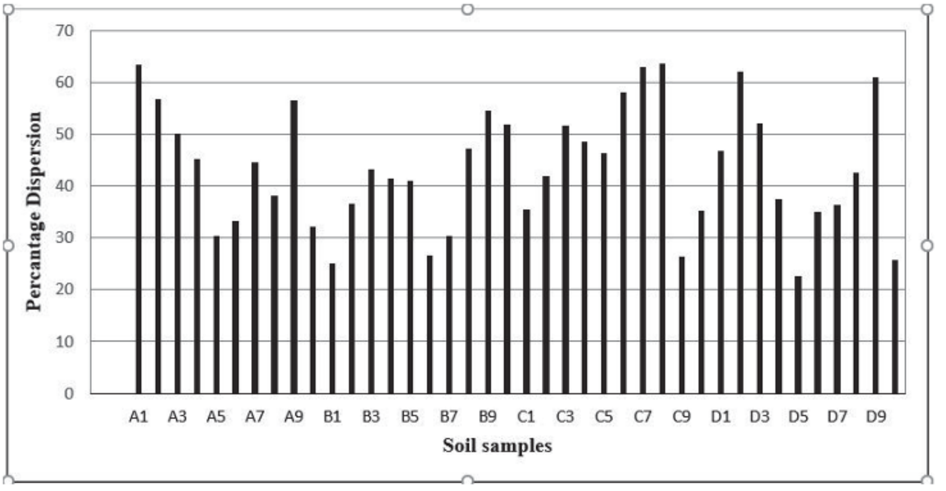

Figure 10.
Double hydrometer test results.

The linear shrinkage computed from the soil samples ranged between 10.53 and 20.76 (**Table 2**). The computed weighted plasticity index (PI_w) from the analysed soil materials ranged between 17.92% and 34.92%, averaging 28.4%.

The computed weighted plasticity index for most of the tested soils is above the 20% threshold for expansive soils, signifying highly unstable soils. All the tested samples had expansiveness (ε_{ex}) between 20 and 50 indicating medium expansive soils which are highly vulnerable to slope failure. More than 90% of the analysed samples have expansiveness above the 20% threshold. More than 80% of the samples have values between 20 and 50% showing medium expansive soils (**Table 2**).

3.5 Shear strength parameters

Shear strength parameter test results show that the soils have low cohesion (C). From the samples analysed, soil cohesion ranged between 5.2 kPa and 11.1 kPa averaging 8.2 kPa. The angle of internal friction obtained from the analysed soil samples ranged between 2.6° and 8.1° averaging 5.4° (**Table 2**). From the soils completely saturated with water, a lower cohesion of 5.2 kPa was detected. A minimal cohesion value of 8.2 kPa was considered as the critical state equilibrium all over the area. This is due to the fact that slope failure is expected to occur when soil materials are saturated. The present study established that most of tested soil samples had a very low internal friction angle (<8.5°). Such soil materials with very low internal friction angle were considered weak with high vulnerable to landslides.

3.6 Soil water infiltration

High infiltration rates were observed in the top soils with depth ranging from 0.3 to 0.8 m, but drastically reduced in the sub soils. Steady infiltration rates greatly varied with topographic characteristics and land use/cover types. Higher infiltration values were noticed in the lower slope elements than the upper sections (**Figure 11**). From the infiltration experiments conducted, it was revealed that the average soil-water infiltration was 24 cm/h^{-1} in uppermost slope sections. On the upper-middle, lower-middle slope sections and bottom valleys, soil-water infiltration rates of 30 cm/h^{-1}, 70 cm/h^{-1} and greater than 80 cm/h^{-1} respectively were achieved from the experiments conducted. Along the hollows within the upper slope sections, the

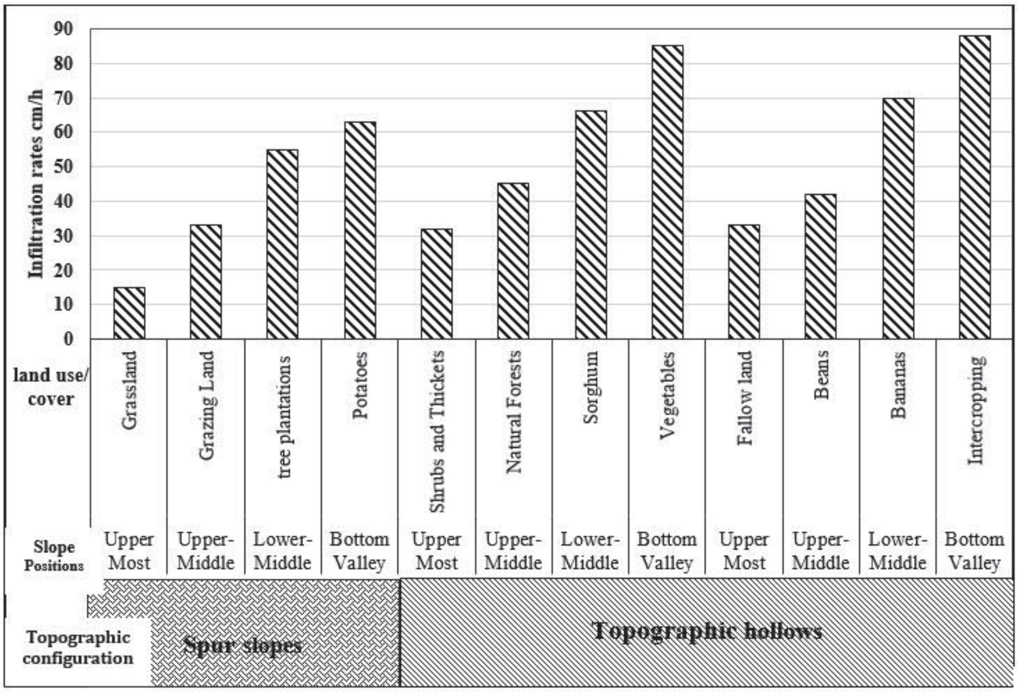

Figure 11.
Infiltration rates along slope positions, topographic configurations and land uses/covers.

observed infiltration rates were greater than 30 cm/h^{-1} and less than 12 cm/h^{-1} along the spur slope sections. Whereas the infiltration rates within topographic hollows along the middle slope sections was greater than 70 cm/h^{-1}, it was less than 45 cm/h^{-1} on the spur slope elements (**Figure 11**). Within the top soil layers, high infiltration rates are explained by the dominancy of loamy sandy soils. The predominance of clay materials in the subsoil, with claypans distinctly underlying the top soils, limits water infiltration in the study area. Such soil characteristics affect their response to incoming rainfall and consequently the timing of landslides, as explored in the discussion section.

The land use and cover characteristics influence soil water infiltration in the study area. Within the agricultural land uses particularly along cultivated zones, infiltration rates were noticed to be higher than those observed on natural land cover types. The infiltration rates along the agricultural land uses were generally greater than 65 cm/h^{-1} with the exception of beans covered areas where infiltration rates were noticed to be lower than 42 cm/h^{-1}. On the natural land cover types including grasslands, thickets and shrubs, infiltration values lower than 30 cm/h^{-1} were generally observed (**Figure 11**). Areas covered by forests, however, tended to have infiltration values higher than 45 cm/h^{-1} (**Figure 11**). Basing on these results, it was deduced that infiltration values in the study area vary greatly between rapid and very rapid. They also vary with slope characteristics including gradient and curvature as well as land use and cover properties. Following the experiments conducted, it was concluded that the steady state water infiltration values in the study area range from 12.2 cm h^{-1} to 88.5 cm h^{-1}.

3.7 Rainfall distribution and soil behaviour

The behaviour of soil materials and its susceptibility to landslide occurrence greatly depends on rainfall amounts and distribution in the region. During the

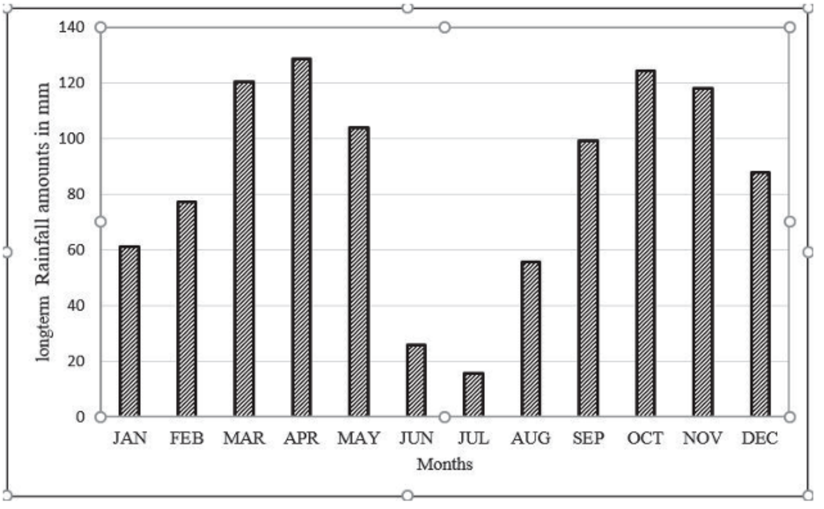

Figure 12.
Long term average monthly rainfall distribution for 1980 to 2020.

analysis of landslide occurrence, considering the influence of soil antecedent moisture and its implication on soil pore water pressure is very important. Monthly rainfall distribution shows that March, April, October and November are the wettest months in the study area (**Figure 12**). Rainfall amounts and distribution have great implications for soil behaviour and hence landslide occurrence in the study area. Seasonal rainfall distribution shows more rains are received during the MAM (352.5 mm) and SON (327.8 mm) seasons, while DJF (238.4 mm) and JJA (104.72 mm) seasons receive less rainfall (Appendix 2). It is noteworthy, however, that landslide occurrence in the study area is not linked to individual rainfall events, but correspond with seasonal rainfall distribution.

Following an interaction with the local communities as well as local government reports, it was established that most of the landslides are experienced during months of May and November. These are, however, not the wettest months in the region (Appendix 2). In 2010, for example, more landslides occurred during the month of May which, however, received lower rainfall amounts (97.7 mm) compared to the preceding months of March (149 mm) and April (133 mm). During 2013, landslides were similarly experienced during the month of November with lower rainfall amounts (122. 2 mm) compared to the preceding months of September (134.1 mm) and October (154 mm) (Appendices 2 and 3). It is therefore, noteworthy that landslides in the study area do not necessarily occur in the wettest months of the year. The implications of this phenomenon is unravelled in the subsequent section.

4. Discussion

4.1 Soil profile characteristics

Deep soil profiles ranging between 2.5 and 7 m are a major characteristic of the study area. Deeper soil profiles are more pronounced along topographic hollows and valley bottoms. Soil depth forms one of the conditions for assessing the stability of the soil materials and landslide susceptibility of the landscape [40]. Soil depth and its moisture content determine how water can be stored in the soil before saturation is reached [41]. Although most of the ridges in the study are characterised by deep to very deep soils profiles (greater than 6 m on most slopes), majority of the landslide features are shallow, concentrating within 1 to 3 m of the profile. Shallow landslide scars are not uncommon in slope sections covered by deep and very deep soil materials. As has been illustrated by [7], most sections covered by deep soils on the slopes of Mt. Elgon in Eastern Uganda experience deep seated landslides. Shallow landslides on deep soil covered slopes in the Kigezi highlands was, therefore, considered as an anomaly. Soil profile analysis was undertaken to establish the cause of this irregularity. The profile characterisation indicated the existence of 0.9 to 3 m dense claypans within the profiles. Following the infiltration experiments conducted, it was established that claypans decreased the rate of water infiltration within the soil materials. The restraint of perpendicular water flow within the soil materials by claypans has also been confirmed by [42]. The accumulating water leads to saturation of claypans sandwiched between more stable materials. Saturated claypans can act as a sliding surface for the overlying materials, consequently inducing landslides. Other studies elsewhere also confirm that variations of claypan profile properties over the landscape greatly influence soil-water holding capacity [35, 43]. It can, therefore, be inferred that the occurrence and characteristics of landslides in Kigezi highlands is highly influenced by the presence and position of claypan horizons within the soil profile.

4.2 Particle size distribution

Fine-grained silt and clay soils predominate the study area. From the mechanical analysis conducted to determine soil particle sizes, it was established that clay is the dominant material, with greater than 40%. The distribution of sand and silt in the soil materials was less than 35% and 25% respectively. The soil materials in Kigezi highlands can be classified as Vertisols due to the high clay content of more than than 35% on average and plasticity index (PI) greater than 33%. Such soils are known for inducing landslides [1]. Vertic soils characteristically expand when wet and shrink in dry conditions due to their high clay content [9]. The presence of large amounts of clay in soils of the study area is a major factor in landslide occurrence, since it affects the stability of the soils when wet. Likewise [7], also observed that the susceptibility to landslide occurrence on the slopes of Mount Elgon is due to abundance of fine-grained materials in the subsurface. The study results are, therefore, consistent with several studies elsewhere which have demonstrated the influence of high clay content on landslide occurrence [1, 18, 44].

4.3 Clay mineralogy

XRD Clay mineral analyses indicated the presence of moderately expansive clays, particularly illite/muscovite. Previous studies indicate that the presence of illite clays can lead to landslide occurrence due to their swelling potential and low shear strength [10, 45]. In the same vein [7], also confirmed that the occurrence of landslides on Mount Elgon slopes in Eastern Uganda is associated with the existence of greater amounts of kaolinite and illite clay minerals in the soil materials. The existence of significant amounts of illite/muscovite clay minerals in the study area further confirmed that Vertisols with high shrink-swell properties can result into landslides. The behaviour of the soil materials greatly determine the timing of landslide occurrence during rainfall seasons. There is fast flow of water through the surface soil materials with greater amounts of quartz into the deep soil profiles with clay abundance at the start of the rainfall season. Greater amounts of illite/muscovite clay minerals in the subsurface absorb the arriving water resulting into moisture build-up. The amassing water in the soil materials leads to soil behavioural change which can swell and loose cohesion [46]. This phenomenon, therefore, explains why landslides in the study area are not experienced at the beginning of the rainfall season or immediately after extreme rainfall events, as is the case with Mt. Elgon region in Eastern Uganda.

4.4 Soil dispersion

The study area is characterised by soil materials associated with high plasticity and are, therefore, inorganic in nature (CH), signifying weak soils of high saturation (**Figure 7**). Results from soil dispersion tests revealed high plasticity index of greater than 30% signifying Vertic soils. During continuous rainfall events, such soils with high plasticity can easily slide. The LLs for all samples analysed was above 50%, signifying high plasticity. Following soil expansiveness analysis, it was established that the average weighted plasticity index (PI_w) and expansiveness were 26.4% and 32.8% respectively. By implication, such soils are highly dispersive and excessively susceptible to landslide occurrence [10]. Landslide occurrence in the study area is, therefore, associated with expansive soils which shrink and swell leading to loss of soil strength. The expansive potential of the soils influenced by high clay content and type especially illite/muscovite is one of the major factors promoting landslides in Kigezi highlands.

4.5 Soil water infiltration

Soil water infiltration was noted to vary across slope position and topographic configuration. Whereas upper slope sections and spur slopes with shallow soils experience low infiltration rates, lower slope sections and topographic hollows with deeper soils are associated with high infiltration rates. This variation in infiltration rates also signifies differences in soil saturation levels ("For example, see [47]"). The lower slope sections are associated with greater saturation rates which result into saturation overland flow processes. Along the topographic slope elements, the saturation overland flow incrementally moves upslope from the slope base [48]. Materials along topographic hollows remain saturated most times due to greater clay content dominated by illite/muscovite minerals. This phenomenon leads to decreased soil material strength along the topographic hollows, inducing landslide occurrence. Equally noticed in this study was a relationship between topographic characteristics and soil water infiltration. Greater soil-water infiltration values are experienced along topographic hollows and lower slope elements than the spurs and upper sections. Such variations in infiltration values in relation to topographic characteristics are associated with differences in soil depth along the slope configurations. This study, therefore, approves that using the soil-water infiltration experiments along different slope sections and gradients it is possible to predict landslide occurrence.

4.6 Change in soil behaviour with rainfall distribution

As opposed to the situation on the slopes of Mt. Elgon in Eastern Uganda, landslide occurrence in Kigezi highlands is not related to extreme rainfall events. On the slopes of Mt. Elgon in Eastern Uganda, majority of the landslides are commonly witnessed during or immediately after extreme rainfall events [1, 7, 18]. Local communities and regional government reports confirmed that landslide occurrence in the study area is usually not experienced during or immediately after peak rainfall seasons. Paradoxically, they occur during the less wet months of the rainfall season. Most landslides in the study area are experienced during the months of May and November, despite the preceding months of April and October receiving more rainfall amounts. This phenomenon can be explained by the unique infiltration dynamics through quartz dominated top soil layers and saturation of the claypans dominated by illite/muscovite clays in the lower soil horizons. This leads to antecedent moisture building up in the sub soil materials as more rainfall is received hence landslide occurrence in the region. Antecedent soil moisture condition prior to a rainfall event has been confirmed as the most significant factor in landslide occurrence [49].

5. Conclusion

Deep soil profiles are a major characteristic of the study area. Notwithstanding the deep soil profiles on most slope elements in the study area, majority of the landslide scars are shallow, occurring within less than half of the profile due to presence of claypans. The claypans act as a slipping zone for the overlying soil materials. The study area is dominated by fine silt and clay soil materials. In association with greater amounts of clay percentage of more than 35% on average and PI greater than 33%, the soil materials in the study area are classified as Vertisols, which are synonymous with landslide occurrence. The predominance of reasonable amounts of expansive clays, mainly illite in the study area influences the stability and vulnerability of slope materials to landslide occurrence. In Kigezi highlands, landslides are not normally experienced during or immediately after extreme rainfall events but occur later in the rainfall season due to initial infiltration through quartz dominated upper soil layers, before illite/muscovite clays in the lower soil horizons get saturated. This behavioural change in the soil material due to moisture content is, therefore, the major trigger of landslides in Kigezi highlands. An understanding of these soil characteristics is an important step in landslide hazard mitigation in Kigezi highlands.

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Conflict of interest

The authors have no conflict of interest.

Appendices

Appendix 1. Soil morphological characteristics

Landslide site	Soil profile	Gradient (°)	Soil depth (m)	Location of clay pan	Horizon A (m)	Percentage distribution			Horizon B (m)	Percentage distribution			Horizon C (m)	Percentage distribution		
						Sand	Silt	Clay		Sand	Silt	Clay		Sand	Silt	Clay
1	P1	38	0.92	0.55	0.61	44	33	23	0.82	28	24	48	0.88	12	28	60
	P2	31	1.72	1.02	0.75	44	32	25	1.21	27	25	48	1.55	18	31	51
	P3	21	3.32	1.17	1.17	54	23	23	1.94	21	23	56	2.94	23	27	50
	P4	9	5.11	3.14	1.44	38	34	28	2.82	22	16	62	4.12	21	26	53
2	P5	47	0.71	0.43	0.67	40	31	29	0.69	23	24	53	0.7	20	25	55
	P6	26	2.12	1.22	0.82	33	40	27	1.44	29	25	46	2.02	18	19	63
	P7	18	3.83	2.16	0.93	38	32	30	2.11	30	24	46	3.21	22	26	52
	P8	10	6.21	3.11	1.11	42	30	28	3.21	21	17	62	4.23	17	22	61
3	P9	34	0.62	0.72	0.62	39	36	25	0.92	24	21	55	1.22	23	26	51
	P10	28	2.03	1.44	0.74	42	31	27	1.23	28	25	47	1.95	21	26	53
	P11	21	3.92	2.82	0.92	35	37	28	1.94	19	33	48	3.32	19	27	54
	P12	11	5.82	3.32	1.23	40	34	26	3.11	24	20	56	4.74	21	30	49
4	P13	48	0.78	0.69	0.65	43	36	21	0.75	28	27	45	0.91	23	27	50
	P14	30	1.83	1.12	0.82	44	30	26	1.22	22	14	64	1.73	19	37	44
	P15	16	3.41	1.92	0.93	43	32	25	1.88	21	29	50	3.11	22	23	55
	P16	8	6.34	3.17	1.13	40	34	26	3.11	31	18	51	5.44	20	27	53
5	P17	43	0.65	0.73	0.61	41	33	26	0.82	25	28	47	1.11	21	22	57
	P18	31	1.74	0.93	0.73	44	32	24	1.44	20	28	52	1.72	22	25	53
	P19	19	3.12	1.83	0.84	45	32	23	2.11	24	26	50	2.88	18	28	54
	P20	7	6.81	3.24	1.06	47	30	23	3.33	26	30	44	5.81	21	25	54

Landslide site	Soil profile	Gradient (°)	Soil depth (m)	Location of clay pan	Horizon A (m)	Percentage distribution			Horizon B (m)	Percentage distribution			Horizon C (m)	Percentage distribution		
						Sand	Silt	Clay		Sand	Silt	Clay		Sand	Silt	Clay
6	P21	46	0.87	0.61	0.66	44	31	25	0.93	23	30	47	1.31	20	27	53
	P22	29	2.31	1.22	0.81	50	32	18	1.71	25	27	48	2.11	19	20	61
	P23	15	4.12	2.12	1.22	42	22	36	2.34	22	36	42	3.88	19	31	50
	P24	11	7.12	3.11	1.54	40	28	32	3.33	21	18	61	4.78	22	29	49
7	P25	44	0.93	0.82	0.77	52	32	16	0.87	27	23	50	0.93	23	19	58
	P26	33	2.21	1.36	0.88	43	29	28	1.32	26	24	50	2.01	16	34	50
	P27	18	3.36	1.97	0.91	46	36	18	2.11	22	31	47	3.12	23	25	52
	P28	13	6.61	3.92	1.22	55	35	10	3.42	18	36	46	4.68	18	36	46
8	P29	42	0.96	0.78	0.71	50	35	15	0.88	31	23	46	0.97	21	26	53
	P30	25	2.42	1.44	0.92	44	37	19	1.94	28	23	49	2.11	22	28	50
	P31	20	4.21	2.33	0.95	48	30	22	2.88	30	25	45	3.89	18	21	61
	P32	12	7.21	3.12	1.23	47	37	16	3.44	22	36	42	5.88	20	27	53
9	P33	48	0.83	0.48	0.66	49	33	18	0.84	30	21	49	0.95	23	26	51
	P34	28	1.94	0.78	0.77	42	36	28	0.91	28	21	51	1.44	19	27	54
	P35	22	3.56	2.21	0.93	53	31	16	2.45	27	25	48	3.22	18	30	52
	P36	8	6.72	3.37	1.11	50	27	23	3.11	19	37	44	5.77	19	24	57
10	P37	45	0.94	0.53	0.71	44	33	23	0.88	29	23	48	1.17	21	24	55
	P38	34	2.44	1.52	0.93	40	33	27	1.98	23	27	50	2.23	23	20	57
	P39	17	4.23	2.17	1.03	48	33	19	2.44	17	20	63	4.11	22	21	57
	P40	11	6.83	3.13	1.33	45	30	25	3.12	18	35	47	5.88	22	18	60

Appendix 2. Temporal distribution of rainfall in Kabale highlands

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1980	56.6	75.3	51.8	164	188	5.3	8.2	39.4	103.3	111.4	137.5	47.8
1981	67	16.7	147.8	138.2	102.8	22.4	7.3	128.8	58.2	122.4	58	74.7
1982	18.9	8.3	42.7	272.2	131.9	15.5	7.5	2.8	107.6	123.4	167.5	22.3
1983	13.4	51.8	88.7	126.3	45.2	12.5	19.2	88.4	70.4	236.5	74.3	95
1984	37.2	108.3	175.4	157.3	20.3	11.2	49.7	21.6	78.8	113.7	97.2	128.2
1985	32.4	34.7	103.4	148.5	40.6	2.8	12.2	23.8	90.4	122.4	72.5	37
1986	0	0	102.6	184	64.3	31.7	18.2	16.4	44.3	121.7	71.1	488.4
1987	82.7	99.2	113.5	131.1	178.4	44.6	3.9	23.3	108	129.1	261.5	31.3
1988	83.9	90.9	161.7	139.1	82.2	4	64.2	142.6	166	132.8	60.8	47
1989	34.7	99.8	82	89.6	134.9	35.6	10.1	74.7	180.8	128.5	72.3	74.3
1990	49	161.8	128.4	182.6	72.6	0	0	45	158.5	66.5	93.6	68.9
1991	72	73	158	101	117	39	18	18	54	135	51	71
1992	18	49	151	98	50	54	27	16	149	205	89	74
1993	96	28	176	87	160	34	0	61	10	59	95	77
1994	58	70	128	150	87	2	2	79	148	125	134	93
1995	45	128	105	82	147	123	1	6	114	166	105	102
1996	70	56	146	93	46	72	50	118	123	144	202	102
1997	101	0	114	122	149	33	27	37	25	155	196	151
1998	184	97	101	171	170	19	25	23	87	154	58	80
1999	77	37	145	72	51	0	0	167	65	87	116	49
2000	50.9	83.5	118.9	120	55.7	8.1	5.9	69.6	69.9	179.8	146.8	83.8
2001	86.3	51.2	83.9	135.7	77.8	22.4	46.7	65.7	231.1	201.9	139.5	63.9
2002	120.2	89.7	63.1	74.9	115.7	0	4.4	48.4	49.5	187.6	91.5	91
2003	66.9	80.6	74.7	139.1	96	29	22.8	25.5	82.6	86.5	94	57.3
2004	69.4	93.8	84.5	183.2	84.6	0	1.1	31.9	148.8	76.9	114.2	124.9
2005	25.7	121.8	170.1	123.4	122.1	40.5	0	29	84	107.6	66.1	41.1
2006	85.5	133.5	127.7	112.7	207.8	2.9	30.1	79.5	74.2	70.7	156.2	62.3
2007	55.2	102.5	80.3	103.6	87.9	34.1	42	23.6	99.5	112.1	162.9	25.2
2008	99	65.3	206.1	54.2	53.5	65.9	24	36.5	77.4	172.8	107.6	99.1
2009	61	114.2	122.7	99.5	90.7	19.8	1.1	94.6	87	86.6	174.1	98.8
2010	97.7	189	149.1	132.9	97.7	9.3	1.4	16.4	124.1	197	86.4	71
2011	33.5	64	139.2	88.2	63.9	62.5	12.1	103.8	71.7	73.9	157.5	54.7
2012	2.8	52.8	110.6	197	146.8	11.6	9.4	62.6	95.7	114.4	179.8	128
2013	30.1	101.1	142.2	98	192	21.1	3.2	74.5	134	154	122.2	77.1

Source: Kabale meteorology station, weather data: WMO No. 63726, National No. 91290000, station name KABALE, Elevation 1867 m, Latitude 01°15′, Longitude 29°59′.

Appendix 3. Relationship between seasonal rainfall distribution and landslide occurrence

Year	Season	Rainfall in mm	No of landslide occurrences	Month of occurrence
2005	MAM	414.6	6	May
2006	MAM	447.2	5	May
2007	MAM	272.8	5	April
2008	MAM	464.8	13	May
2009	SON	348.7	5	October
2010	MAM	457.7	31	May
2011	MAM	461.2	22	May
2012	MAM	453.4	8	May
2013	SON	304.1	5	November
2014	SON	253.2	3	October
2015	MAM	254.7	17	May
2016	SON	298.3	9	October
2017	MAM	213.8	11	May
2018	MAM	417.8	21	April
2019	SON	314.7	13	November
2020	MAM	339.9	17	May

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