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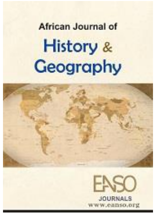

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Original Article

Elevation and Slope as Key Determinants of Landslide-Prone Areas in Murang'a County, Kenya

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ABSTRACT

Landslide studies in Kenya have received less interest as opposed to other regions of the world. Murang'a County in Central Kenya presents a unique case of geographical interest not only due to its positioning within the alpine Aberdare Ranges but also because it has experienced serious, deadly and repeated landslide disasters. This study seeks to ascertain whether elevation and slope are key determinants of landslide in the county. Primary data collection instruments were Household (HH) questionnaires where a sample size of 393 HH was sampled at a confidence level of 95%. Secondary data for elevation and slope were derived from satellite imagery. A significant 95.5% of the respondents said that slope was a major landslide causal/trigger factor. A significant number of people (r=0.806) who had migrated to their current locations described steepness as a major causal/trigger factor. Elevation factor was mentioned by 90.2% of the respondents as a key factor contributing to the occurrence of landslides. The study concludes that elevation and slope are key and significant landslide causal/trigger factors in Murang'a County. The study recommends that people living in areas delineated as 'high-risk zones' should be advised to relocate to safer grounds to avert huge losses from potential landslide disasters.

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INTRODUCTION

Generally, the term landslide refers to the various types of downward and outward movements of slope materials such as soils/earth, rocks, debris and other ground materials either in fast or slow motion. The earth's materials may flow, fall, creep, topple, slide, spread or undergo a combination of these processes (Highland, 2006). A landslide is a type of mass movement or mass failure (Gorsevski *et al.,* 2005), a geomorphic process which affects steep slopes worldwide (Westerberg & Christiansson, 1999) and which may have different characteristics from place to place (Van Westen *et al.,* 2006). The occurrence of a landslide is subject to the energy from the environment and the state of causal/trigger factors (Yufeng & Fengxiang, 2009). Landslide events are subject to a variety of factors which in turn result in different types of landslides in terms of slope failure type, magnitude and spread (Glade, 2003; Glade *et al.,* 2006*;* Uzielli *et al.,* 2008; Fell, 1994*).* Types of landslides may be characterized and categorized according to the type of materials in question and how they are moved (Maina-Gichaba *et al.,* 2013), dynamics and types of slope failure (Highland *et al*., 2008).

Landslides account for a significant part of major natural disasters and usually occur in mountainous regions, but can also happen in low-elevation areas for instance slope failures in cliffs or cut and fill materials (Maina-Gichaba *et al.,* 2013). Landslides are highly localized as they occur in small geographical extents and are viewed as a system comprising sub-systems characterized by causal/trigger factors (Shi, *et al.,* 2020; Khasanov, *et al.,* 2021). Mountainous regions are normally characterized by high elevation and slopes. The existence of slopes is one of the main causal factors for landslide occurrence in many parts of the world (Othman *et al*., 2012; Van Westen, 2006). For instance, slope as a key factor has been cited in a study which analyzed fifty-six landslide research publications (between the years 2000 and 2020) in Central Asia and found that forty-two (42) out of seventy-nine (79) Scopus peer-reviewed and published papers, accounting for 53%, cited slope as being a main cause/trigger factor for landslide occurrences (Khasanov *et al.,* 2021). Nevertheless, the slope factor works alongside other causal/trigger factors for the occurrence of a landslide.

Landslide studies in Kenya have received less interest compared to other regions of the world (Maina-Gichaba *et al.,* 2013). Landslides in Kenya are mostly recorded in Central Highlands, Rift Valley and Western parts (Nyaoro, *et al.,* 2016) characterized by high rainfall regimes, mountainous terrains, deep volcanic soils and high population densities (Mines and Geology Department, 2012). Actions of water and human activities on sloping grounds have been reported in Kenyan Highlands where landslides occur in slopes with a gradient of 25^{o} or above (Wahlstrand, 2015). Thomas (1974) opined that mass movements in tropical areas are generally confined to slopes of between 30^{0} and 60^{0}. It is believed that most of the *El-nino* rains-induced landslides occurred due to high relief in the affected regions (Ngecu & Mathu, 1999). Due to increased soil moisture and saturation in the hilly areas as a result of heavy rainfall, slope failures occur as a result of the weakening of the slope stability courtesy of increased soil wetness (Huho *et al.,* 2016).

Landslides in Murang'a County, located in the Central part of Kenya, presents a unique case of geographical interest. This is due to two main reasons. Firstly, due to the geographical location of the county within the Alpine Aberdare Ranges, a region with favourable landslide causal/trigger factors. The factors include high altitude characterized by intensive rainfall, steep slopes, loose soils and vulnerable land-use land cover types (Njiraini *et al.,* 2022). A comprehensive study in the county done in the case of the 1997 Muringa village landslide showed that other than the heavy rainfall in the year, geology, climate and soils were other major contributing factors. The landslides occurred in the heavily weathered pyroclastic regolith and deep red andosols found on highly unstable slopes which slide over the stable agglomerate under the trigger of heavy rains (Ngecu *et al.*, 2004). The second reason is that of all the counties traversed by the Aberdare

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Ranges, Murang'a County has had the most serious, deadliest and repeated landslide disasters in the recent past, (Salome *et al.*, 2004, KMD, 2022). The landslide is termed as deadly (Ngecu *et al.,* 2004). Despite the two compelling reasons, no comprehensive landside disaster study has been done in Murang'a County specifically around the geographical feature and area, the Aberdare Ranges.

Objective of the study

Kenya is a country susceptible to disasters and landslides are among the deadliest and recently recurrent disasters in Murang'a County (Salome *et al.*, 2004). The occurrence of landslides in the county is a reality due to the existence of favourable prevailing causal/trigger factors. This study seeks to investigate whether elevation and slope are among the key landslide causal/trigger factors in Murang'a County.

Research Question

Are elevation and slope key landslide causal/trigger factors in Murang'a?

METHODOLOGY

Scope of the study

The study is about landslide disasters as a general mass movement type without differentiating among the various types and forms of landslides within the study area. The study focused on March-April-May (MAM) 2018 historical landslide cases because it represents the period with the highest number of reported landslide cases within a single rainy season (March-April-May) in the history of the recurrent landslides in Murang'a County (KMD, 2021). Finally, the focus is on instances where landslide disasters have occurred and had reported cases of deaths, displacements of people and animals, and destruction of goods and properties.

The study area

Murang'a County is in the central part of Kenya, a country found in East Africa. The county is spatially expansive, spanning from an alpine zone defined by a tropical forest called the Aberdare Forest to semi-arid zones bordering Machakos and Embu Counties. Murang'a altitude ranges from 914 meters Above Mean Sea Level (AMSL) in the lowlands East and 3,354 meters AMSL in the highlands west along the slopes of the Aberdare Ranges. The highlands consist of volcanic rocks of the Pleistocene age containing porous beds and disconformities which act as important aquifers and are the origin of many streams while the lowlands have basement rocks of Achaean type. The latter has dissected terrain characterized by valleys and ridges which makes the zones prone to landslides and erosions (CIDP, 2018). The county is divided into six agroecological zones; zone 1 has the highest potential and is covered by forests and tea bushes while zones 2 and 3 are the lowlands East of the Aberdares Ranges and are generally suitable for coffee and dairy farming. The third ecological cohort is made up of zones 4, 5 and 6 comprising arid and semi-arid conditions suitable for irrigated agriculture. Murang'a has three climatic regions namely: equatorial in the west, sub-tropical in the central and semi-arid in the eastern end of the county. Kangema, Gatanga, Mathioya, and the upper parts of Kigumo and Kandara are in the western region and are characterized by a wet and humid climate due to their proximity to the Aberdare Ranges.

The Kenyan Central Highlands are densely populated courtesy of fertile soils and favourable climatic conditions for farming (Westerberg & Christiansson, 1999). According to the 2019 Kenya Population and Housing Census (KPHC) by the Kenya National Bureau of Statistics (KNBS), the county has a total land area of 2,524.2 Km^2 with a total population of 1,056,640 and a population density of 419. Total males, females and intersex are 523,940, 532,669 and 31 respectively. The county has a total of 318,105 households (HHs) with an average of 3.3 persons per HH (KNBS, Volume I, 2019). In terms of the population distribution, Gatang'a and Kiharu Sub-counties (Murang'a East and Kahuro) have the largest total number of people compared to the special demarcated zone of Aberdare Forest as shown in Table 1 below.

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Table 1: Population distribution in Murang'a County

Sub-county/Zones	Male	Female	Intersex	Total
Murang'a East	*54,665*	55,645	1	110,311
Kangema	*39,582*	40,862	3	80,447
Mathioya	*45,454*	47,359	1	92,814
Kahuro	*43,352*	44,834	7	88,193
Murang'a South	*91,732*	93,087	5	184,824
Gatanga	*94,437*	93,548	4	187,989
Kigumo	*67,989*	68,929	3	136,921
Kandara	*86,698*	88,393	7	175,098
Aberdare Forest*	*31*	12	-	43

Special census zone** ***Source: **(KNBS, Volume I, 2019).**

Study population and sampling frame

The study area comprised six sub-counties (Kangema, Mathioya, Kiharu/Kahuro, Kigumo, Kandara and Gatanga) which were purposively selected. The study locations were purposively selected from the six sub-counties based on the reported landslide cases for the MAM, 2018 as recorded by KMD, Murang'a County. The study locations had a total population of 85,895 people distributed over 26,201 Households (HHs) (KNBS, Volume II, 2019) as shown in Table 2.

Table 2: Population per location in each study sub-county

Sub-county	Location	Total Population	Total HHs
Kangema	Kihoya	6,423	1,984
	Rwathia	7,417	2,261
Mathioya	Gitugi	7,682	2,308
	Kiru	10,381	3,266
Kiharu/Kahuro	Murarandia	11,880	3,714
Kigumo	Mariira	10,180	3,130
	Kinyona	7,911	2,440
Kandara	Kibage	16,913	4,870
Gatanga	Mbugiti	7,108	2,228
Total		**85,895**	**26,201**

Source: *KNBS, Volume II, 2019*

The sampling frame of the study was Households (HHs) in the landslide disaster-affected administrative locations as per MAM 2018 when the county experienced the largest number of landslide events in history (KMD, 2021). Respondents were the heads of HH who were males or females of mature age. In the cases where HH heads were unavailable, any other person above 18 years of age was selected as a respondent for the HH questionnaires.

Sample size computation

The sample size was calculated using Slovin's (1960) computation formula expressed as follows:

$$n = \frac{N}{1+N\,(e)^2}$$

Where:

N is the total HH number,

n is the sample size,

e is the margin of error at 0.05

n= 26,201/1+26,201(0.05)^2

n=26,201/66.5025= 393

Based on this formula, a sample size of 393 HHS was arrived at (at a confidence level of 95%). Previous studies on indigenous perception and strategies for climate change (Cobbinah & Anane, 2016) have used Slovin's computation to derive an appropriate sample size for a similar target population hence its preference in this study.

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Weighted computations were calculated to standardize the final HHs to be sampled through proportionate HHs for each administrative. The computations were done for each location according to the respective population and the total population for all the target locations (Scheaffer *et al.,* 2011). For proportionate sampling, the below formulae were used:

$$n = \frac{p}{u}$$

Where:

n is the proportionate HHs for each study location

p is the total sample size for a specific study location

u is the total HHs in all study locations

From the proportionate HHs computation, a total of 393 proportionate HHs were to be sampled in the study as computed below for each study location:

Total proportionate HH for Kihoya study location: $\left(\frac{1,984}{26,201}\right) * 393 = 30$

Total proportionate HH for Rwathia study location: $\left(\frac{2,261}{26,201}\right) * 393 = 34$

Total proportionate HH for Gitugi study location: $\left(\frac{2,308}{26,201}\right) * 393 = 35$

Total proportionate HH for Kiru study location: $\left(\frac{3,266}{26,201}\right) * 393 = 49$

Total proportionate HH for Murarandia study location: $\left(\frac{3,714}{26,201}\right) * 393 = 56$

Total proportionate HH for Mariira study location: $\left(\frac{3,130}{26,201}\right) * 393 = 47$

Total proportionate HH for Kinyona study location: $\left(\frac{2,440}{26,201}\right) * 393 = 37$

Total proportionate HH for Kibage study location: $\left(\frac{4,870}{26,201}\right) * 393 = 73$

Total proportionate HH for Mbugiti study location: $\left(\frac{2,228}{26,201}\right) * 393 = 33$

The final stage in choosing respondents for the HH questionnaires was through systematic random sampling of the HHs for the selected administrative locations, starting from a randomly selected HH located centrally within the study location. The preferred starting point was an HH with previously reported landslide cases. The other HHs were randomly selected radially in all directions from the starting point at an interval k^{th} number, which was the 67^{th} HH.

Landslide inventories

Data on the landslide inventories is crucial in assessing, checking and validating the reliability of the outcomes (Zhou, *et al.*, 2020). The landslide inventory data were gathered from the records by Murang'a County Disaster Management offices and County Meteorological Services. Murang'a Meteorological Services (2021) reports indicated that landslides in the county are recurrent and on the upsurge but MAM 2018 had the highest number of reported landslide cases within a single rainfall season, i.e. March-April-May (MAM). This is the reason why the period is considered to be the reference year for the study.

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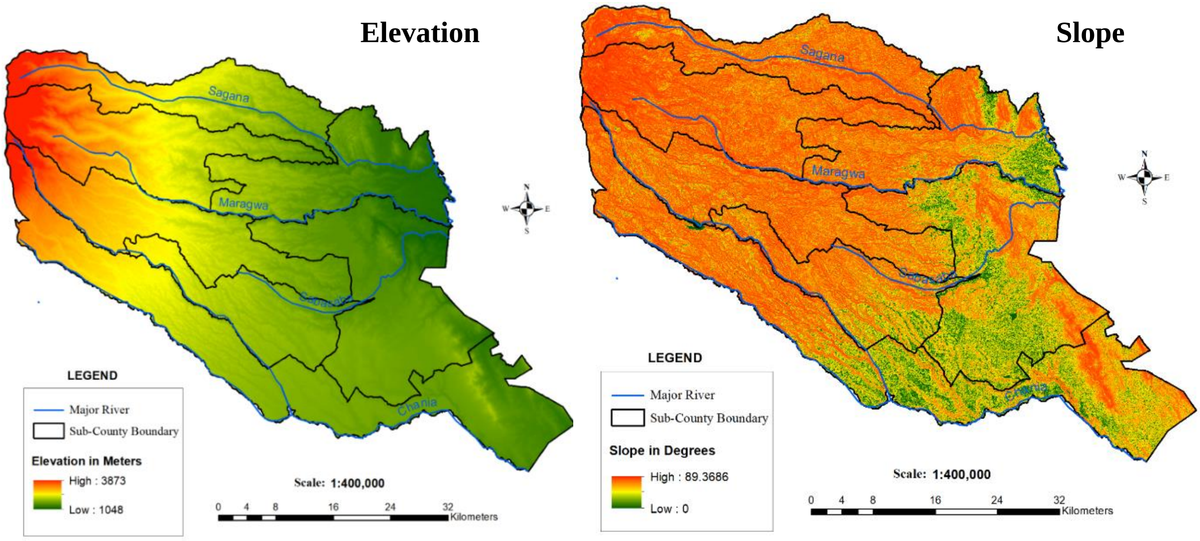
Remote Sensing data on elevation and slope

The elevation and slope data are crucial in landslide research as disasters are known to occur in certain topographies. The data were freely downloaded from the United States Geological Survey's (USGS) Shuttle Radar Topographical Mission (SRTM) through Earth Explorer via https://earthexplorer.usgs.gov/. The study county is in three grids of 1° X 1° tiles: s01_e036, s01_e037 and s02_e037. The resolution for the images was 30 m or 1 Arc Second available over Africa in 1° X 1° tiles released in October 2014 for the whole of Africa. The void-filled SRTM was released by NASA to the world in 2015 (USGS, 2015). The study area spans between elevations of 1048 m to 3873 m AMSL stretching from the lower elevation lowlands to the high elevation alpine zones along the Aberdares Ranges. The slope data was derived from the Shuttle Radar Topographical Mission-Digital Elevation Model (SRTM-DEM) through ArcGIS's 3-D analyst tools and the slopes computed in degrees, range from 0^0 in flat areas to almost 90^0 in the steep areas. See the data in Figure 1 below.

Figure 1: Elevation and slope data for Murang'a County:



Note: Data from USGS (2015) and Google Earth (2021)

Remote sensing data treatment

The remote sensing grid data was georeferenced in GeoTIFF format. The slope grid was converted from degrees to radians because ArcGIS trigonometric tools use radians as opposed to degrees. The conversion was done using the formulae:

$$slope\ Grid\ in\ Radians = Slope\ Grid\ in\ Degree * \pi/180$$

Where:

$$\pi\ is\ Pi = 3.142$$

The two sets of data (slope and elevation) were checked for polarity to ensure that low grid values and high grid values should represent risks and high-risk areas respectively for the slope and elevation. Later standardization was done to put the grids on the same measurement and evaluation scale of between 0 and 1. Standardizing was done in the GIS raster calculator using the formulae:

$$(original\ grid - minimum\ value)/(maximum\ value - minimum\ value)$$

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Where *original grid* is the raster image to be standardized from which its *maximum* and *minimum* values are read from the grid and applied in the standardization formulae above.

Reliability of the HH questionnaires

Cronbach's reliability test is considered to be one of the most reliable tests for the HH questionnaires (Cortina, 1993). Cronbach's (1943) test was used to test the reliability of the questionnaires in which the scaled questions were subjected to Cronbach's test to ascertain the actual reliability and internal consistency of the instruments. A total of eight landslide causal/trigger factors were subjected to the reliability test and the results were within acceptable Cronbach's Alpha coefficient range. As a landslide causal/trigger factor, both slope and elevation were rated at 0.802 while their degree of causality was 0.749 and 0.741 respectively. The complete table for all the factors is shown in Table 3 below:

Table 3: Landslides causal/triggers factors' reliability test

Theme	Cronbach's Alpha
As a Landslide Causal/Trigger Factor	
Rainfall	0.810
Slope	0.802
Elevation	0.802
Soil	0.801
LULC	0.777
Vegetation cover	0.787
Infrastructural development	0.797
Population	0.780
Degree of causality	
Rainfall	0.768
Slope	0.749
Elevation	0.741
Soil	0.762
Land use, land cover types	0.716
Vegetation cover	0.723
Infrastructural development	0.726
Population	0.716

Source: Field Data

RESULTS AND DISCUSSIONS

The elevation factor

The elevation of Murang'a County ranges between 1048 m and 3873 m above MSL and stretches from the lowlands to the high alpine zones along the Aberdares Ranges. The scientific understanding of elevation as a landslide causal/trigger factor was guided by the existing scientific literature. Firstly, a study by Mwaniki *et al.* (2011), put a threshold of elevation in causing landslides at 1,600 m AMSL in which regions of higher elevation values were characterized as high landslide risk areas while those with lower values as low-risk areas. The threshold also corresponded with a classification by Zhou *et al.* (2020). Adopting the same criteria, all the mapped high-risk zones in the study fell in the bands of *'high'* and '*extremely high'* landslide risk classification zones in Kenya as per the previous studies. Through elevation zoning, the county is divided into two almost equal zones; low-risk and high-risk zones at 53.3% and 46.7% respectively as shown in Figure (2-a). In ArcGIS's *extract value to points* operation in spatial analyst tools, the spatial location of the MAM 2018 landslide events was evaluated against the scientifically defined landslide risk zones based on the elevation where the low-risk zones were mainly in the lowlands (southern part) while the high-risk zones were in highlands (northern part) except for a few exceptional cases. The results showed conformity

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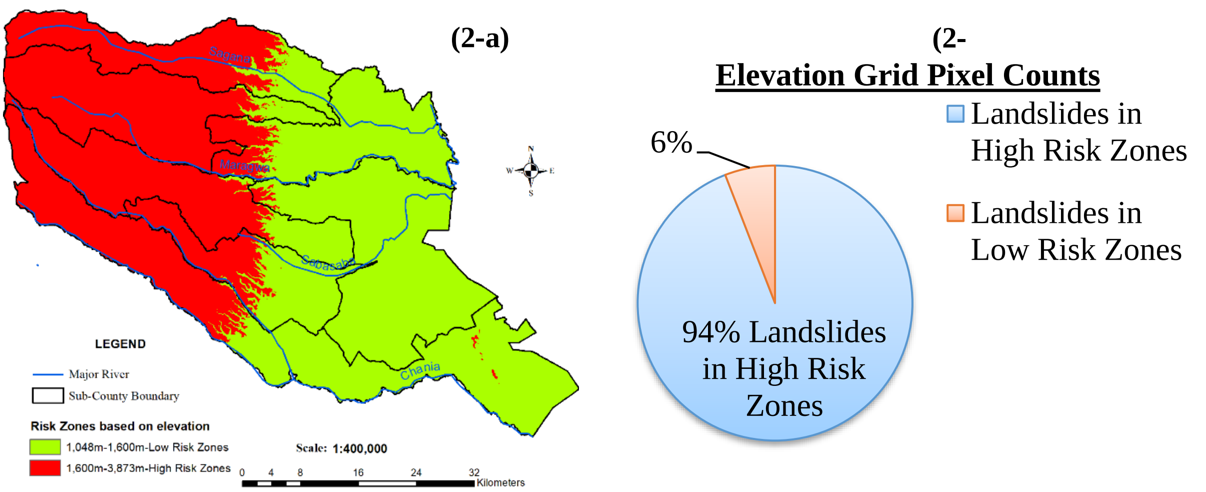
with the reported landslide cases for MAM 2018 where 319 cases, accounting for 94%, fell in the 'high-risk zones' as opposed to 20 cases (6%) which were in the 'low-risk zones' as shown in figure (2-b). It therefore means that elevation is also a key factor in triggering or causing landslides in the area.

Figure 2: Mapped landslide risk zones in Murang'a County based on elevation factor



2-a: Classified and standardized elevation delineated risk zones grid, 2-b: MAM 2018 Reported Landslide cases distribution against the Elevation Delineated Risk zones

The slope factor

For this study, the slope data were derived from the elevation grid through three-dimensional (3-D) analysis in ArcGIS software. Murang'a slopes range between 0 to 89.5 degrees in the flat and high-sloping zones respectively where the most flat areas (least sloppy) have values of zero (0) degrees while the steepest (most sloppy) have values of 89.5 degrees. The scientific mapping of landslide risk zones based on slope causal/trigger factor had a threshold of 60 degrees, with slopes greater than 60 degrees posing high risks compared to the fewer risks for the slopes below that threshold. The thresholding conforms with other scientific studies by Cardinali *et al.*, 2006, Mwaniki *et al.*, (2011) and Zhou, *et al.*, (2020).

The result of the scientific mapping and delineation of landslide zones according to the slope factor resulted in 81.6% of the county's landmass being classified as high-risk zones compared to the low-risk zones covering 18.4%. The high-risk zones are spatially spread almost evenly, especially in the upper parts of the county as shown in Figure (3-a). In comparison with the MAM 2018 reported landslide cases, the resultant slope-delineated landslide zones showed that 95% of the reported cases were in the high-risk zones and only 5% fell in the lower-risk zone as shown in Figure (3-b) below. The results are a good approximation of the landslide disasters for the base period.

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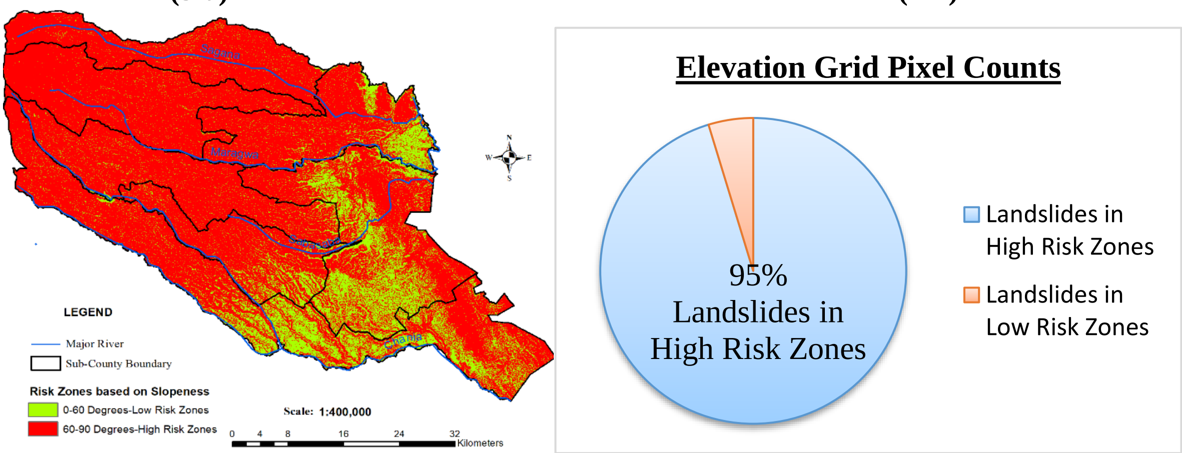
Figure 3: Mapped landslide risk zones in Murang'a County based on slope factor

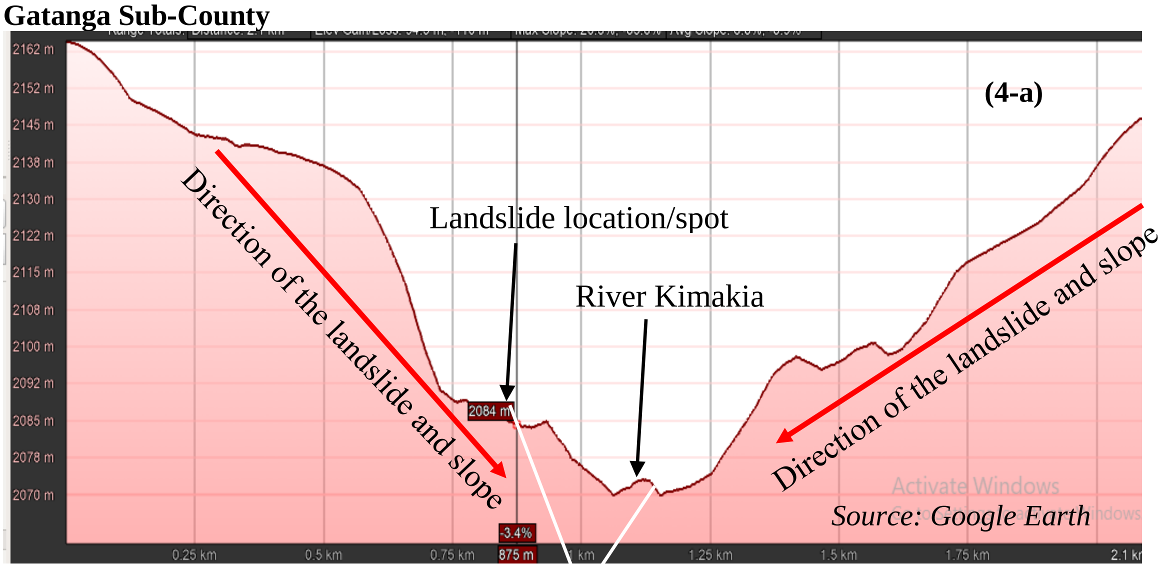
(3-a) **(3-b)**



3-a: Classified and standardized slope delineated risk zones grid, 3-b: MAM 2018 Reported Landslide cases distribution against the Slope Delineated Risk zones

In the study, an epitome of the slope factor was witnessed during the fieldwork in Gatanga Sub-County as shown in Plate 1. In this area, located in Kirangi Sub-Location of Mbugiti Location, a landslide had occurred and swept away tea bush downslope, across a road and down to a nearby River Kimakia. The resultant scars were evidently visible at the time of the fieldwork *(coordinates - 0.844376°, 36.791143°)*, as seen in Figure (4-b). The slope in the area extended from a high of 2,162 m to a low of 2,070 m above msl as shown in the cross-sectional profile in Figure (4-a) and was one of the contributing factors causing the landslide. Of importance to note was the fact that the area experienced a landslide despite the presence of heavy rich vegetation cover.

Figure 4: Slope profile and landslide scar of a landslide site in Kirangi, Mbugiti Location, Gatanga Sub-County



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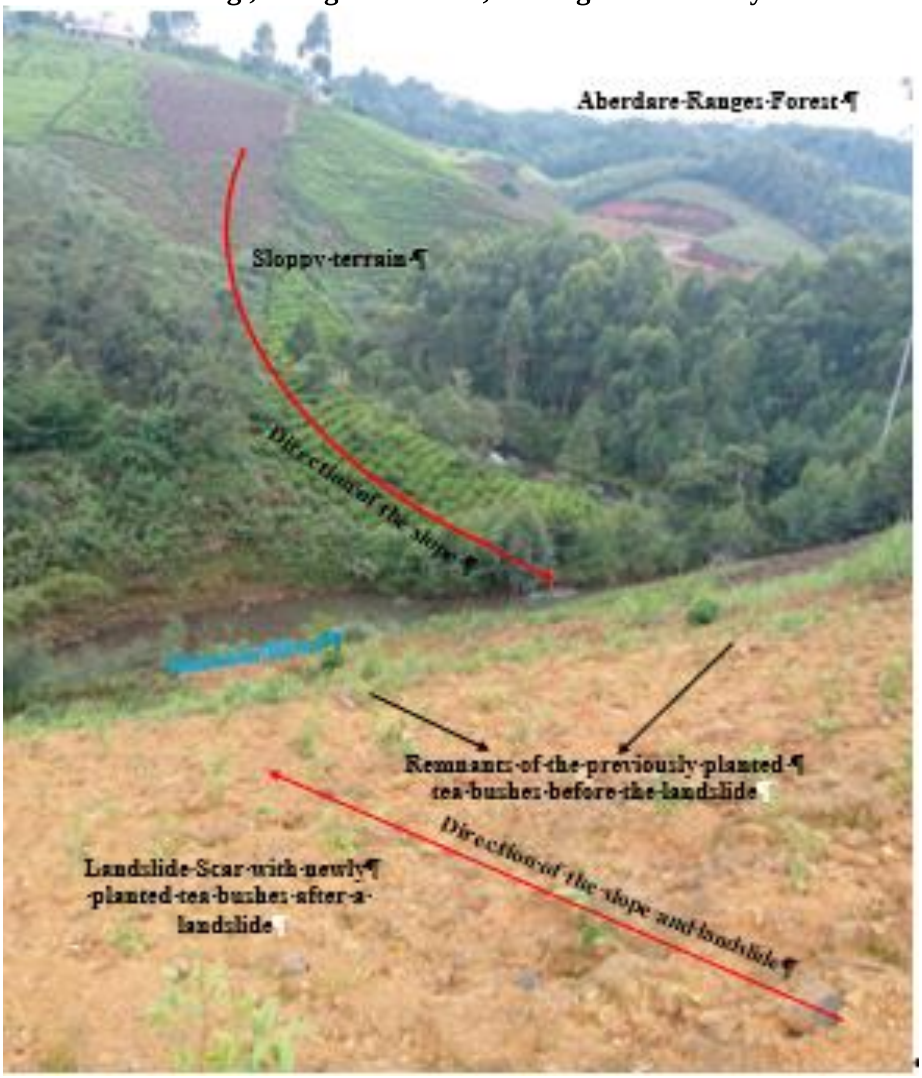
4-a: Digitally generated elevation cross-sectional profile of the landslide area, 4-b: A GE image showing the reported landside spot and the scar

Plate 1*:* The landslide site on sloppy ground where tea bushes were washed down to River Kimakia in Kirangi, Mbugiti Location, Gatanga Sub-County



Source*:* Field Data **(Njira2021**

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Elevation and slope factors in comparison with the 2018 historical landslide cases

The March-April-May (MAM) 2018 historical landslide cases for Murang'a County were overlaid with landslide-prone areas delineated according to elevation and slope among other causal/trigger factors as shown in Table 4.

Table 4: Mapping of landslide-prone areas according to respective factors and conformity with MAM 2018 reported cases

Landslide causal/trigger factor	Conformity with MAM 2018 cases (Percentage)
Rainfall intensity	99 %
Altitude	94 %
Slope	95 %
Soils	88 %
Land use, land cover types	72 %

Source: Field data

Significant convergence of 94% and 95% was recorded for altitude and slope respectively. This means that if all factors were to remain constant, altitude and slope would correctly predict a significant portion of areas which were to have landslides as validated by the MAM 2018 landslide cases.

Local people's understanding and ranking of elevation and slope as landslide causal/trigger factors

Gradient or steepness of the land was also mentioned as a major causal/trigger factor by 95.5% of the respondents. Further in support of that, a significant number of people (r=0.806 at 0.01 level (2-tailed) who had migrated to their current locations described steepness as a major causal/trigger factor. On the same note, a significant 86.2% (r=0.862 at 0.01 level (2-tailed), who reported having experienced a landslide at least once in their home areas also termed slope steepness as a major factor. Elevation factor was mentioned by 90.2% of the respondents as a significant factor in contributing to the occurrence of landslides. The percentage is comparatively lower. Some of the respondents who considered elevation as being less influential in contributing to landslides argued that since elevation rarely changes throughout time, it cannot be considered to be a serious causal/trigger factor, especially in view of the increasing landslide cases in Murang'a amid no change in elevation over time.

CONCLUSIONS AND RECOMMENDATIONS

Available literature in support of slope as a key landslide causal/trigger factor as can be cited from Van Westen (2006) and Othman and others (2012). The sloppy regions of Murang'a County are no exception as stated by Maina-Gichaba *et al.* (2013). The research entitled *"Overview of landslide occurrences in Kenya: causes, mitigations and challenges"* also reported that water-saturated slopes are 'fundamental causes of landslides.' It is also documented that the Central Highlands of Kenya are known for rainfall-triggered landslides due to the 'rugged landscape' (Mwaniki *et al*., 2017) and the upper part of Murang'a is said to be 'deeply dissected' (CIDP, 2018) and mass movement occurs downhill following the force of gravity. These key contentions are in support that Elevation and slope are key landslide causal/trigger factors. The research serves to justify the contention through scientific understanding and as identified and confirmed by the indigenous people of Murang'a County through empirical research. In conclusion, regions above 1,600 m above mean sea level and those with slopes above 60 degrees pose high risks of landslides. People living in areas delineated as high risk should be well advised to take cover especially when other contributing causal/trigger factors come into play. This will help mitigate the adverse effects of landslides on elements at risk.

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