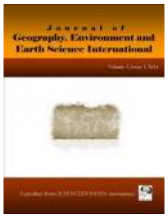

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A Numerical Hazard Rating Method for Debris Slide Susceptibility Mapping in Turkana, Kenya

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Authors' contributions

This work was carried out in collaboration between both authors. Author IEO designed the study and wrote first half of the manuscript. Author CNC managed the literature searches and performed the analysis part. Both authors read and approved the final manuscript.

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ABSTRACT

This study presents a numerical rating method for mapping debris slide susceptibility in Turkana, Kenya. The use of remotely sensed data; 31 m digital elevation model (DEM) 1.5 m SPOT 6 image of study area, and an exploratory soil and agro-climatic zone map of Kenya, (1:1,000,000) were adopted. Numerical hazard rating scheme for testing relationship between debris slide and five event controlling parameters; slope angle, friction angle of soil, soil drainage, soil thickness and proximity to drainage is described. Corresponding thematic data layers were generated for these parameters in ArcGIS. Numerical hazard ratings were assigned to these parameters on a scale of 0 – 5 with 0 being the least susceptible class and 5 having the greatest susceptibility to debris slide. These hazard ratings were justified with the use of the Coulomb Equation of stability analysis. Debris slide susceptibility map indicates that areas close to drainage channels had the highest susceptibility value ranging from 3 – 5. On the hand, areas with no surface material, i.e., bedrock outcrop, and low slope angles had minimal susceptibility value of zero (0). There was no landslide data for the study area and hence the debris slide susceptibility

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map could not be validated. This study therefore has developed a method for debris slide susceptibility assessment that can be adopted in an inaccessible terrain, or in an environment with no landslide data.

Keywords: Debris slide; hazard rating scheme; susceptibility mapping; Coulomb Equation.

1. INTRODUCTION

Increase in population and subsequent urbanization have led to higher demand for residential apartments all over the world. In an effort to fulfil one of the basic needs of humans, which is shelter, developers are driven to construct apartments on marginally stable lands without a full understanding of possible ensuing geohazards that could result from such actions. Landslide processes have been identified as part of normal geomorphic cycle responsible for landscape development in an area [1], yet they become hazardous when they interact with human activities in the affected areas. As a result of pressure on land, search for energy and economic development, new infrastructure is built on mountainsides and steeper slopes thus increasing the threat of landslide hazards and risk to life and property. Hazard can be defined as the probability of occurrence of a potentially damaging phenomenon within an area in a given period of time [2]. Landslide hazards are multifaceted ranging from physical harm to economic challenges, social difficulties to health challenges among others. There are different classifications of landslides. This study focuses on debris-slide (a type of translational landslide) and the production of susceptibility map to define areas most prone to debris slide occurrence, as well as areas with least susceptibility. A debris slide susceptibility map shows relative susceptibility of an area to debris slide occurrence. Studies have been conducted on landslide mapping [3,4], and parameters of interest have been used in these studies. Adoption of the Coulomb Equation of stability analysis for justification of hazard ratings of parameters used in landslide mapping has not always been the case in published literature. This study presents a method based on the adoption of the Coulomb Equation as a numerical paradigm for justification of hazard ratings of parameters of interest in debris slide mapping. Five event controlling parameters (slope angle, friction angle of soil, soil drainage, soil thickness and proximity to drainage) were used for production of debris slide susceptibility map. This was done by applying hazard ratings to these parameters based on their relationship with factor of safety.

The aim of this study is to develop a numerical rating approach to define areas susceptible to debris slide. The following specific objectives are set to achieve the aim; identify terrain of the area, carry out a detailed mapping of terrain units and characterise terrain units based on parameters likely to influence debris slide.

1.1 Study Area

Kenya is dissected longitudinally by the eastern branch of the East African Rift System (EARS), [5]. This branch stretches from the Afar Triangle in the north through the main Ethiopian Rift, the Omo-Turkana lows, down to the Kenya (Gregory) Rifts and ends in the basins of Northern-Tanzanian divergence in the south covering a distance more than 2200 km, [5,6]**.** The study area for this study lies in Turkana Region within the Kenyan Rift with the following geographic coordinates, 1°51'25.03"N and 2°19'33.071"N, and longitude 36°18'0.337"E and 36°18'45.349"E. It covers an area approximately 1036 km^2. It stretches westwards from the rift floor across the western scarp of the Kenya Rift Valley (KRV) in Turkana, Fig. 1 with an elevation ranging from 245 m – 1295 m above sea level.

The climate is semi-arid with temperature over 25°C in the cool months and over 30°C in the hot months, the wet months are between March – May, and October – December with rainfall less than 500 mm in a year, shrubs are the dominant vegetation. The geology, comprises of Cenozoic Volcanics (basalts, andesites, rhyolite, phonolites and undifferentiated lava) and Quaternary sediments [7,8]. Turkana is a seismically active region with a recorded 6.0 magnitude earthquake in 1913 [5]. This geologic condition has the potential to increase susceptibility to debris slide and other types of mass movement.

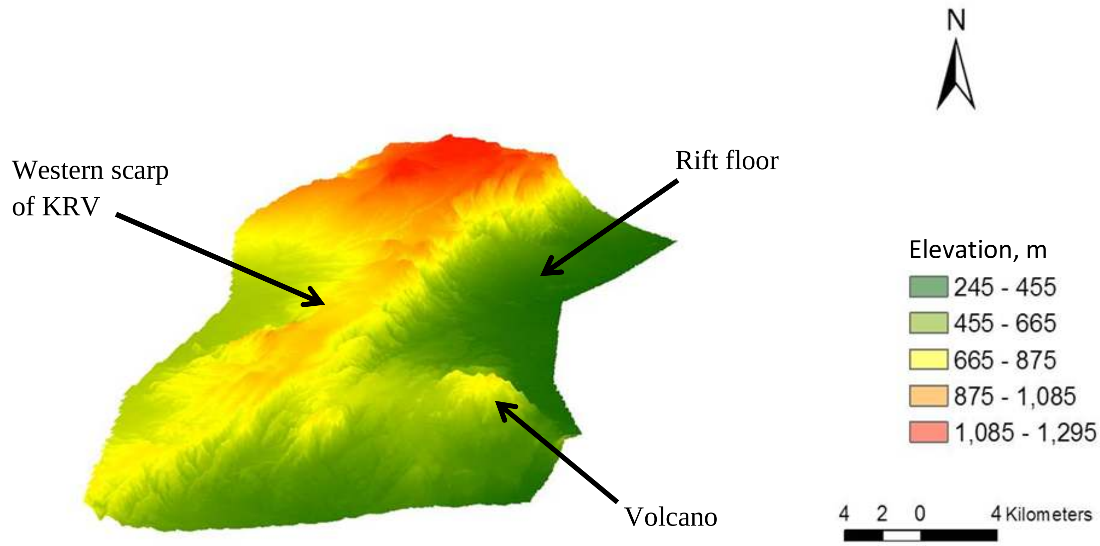

Fig. 1. Vertically exaggerated Arc-scene layer of study area showing volcano, rift floor, and western scarp of the KRV

1.2 Parameters of Special Interest

Landslide studies are well documented in the literature, e.g., [9-13] and factors thought to influence their occurrence vary from natural to human. Some of these factors include slope angle, extreme rainfall, soil characteristics, seismic activities, nearness to drainage channel, deforestation, toe undercutting, as well as construction activities. Slope angle is an important factor of interest in landslide studies. In the Amahata river basin of Japan, [3] reported a dominance of landslide occurrence on slope angles in the 40°– 45° class while [10] opines that debris slides are generally confined to slopes of 15° – 40° and are fairly rapid. Maximum landslide frequency on slope angle of 30° was recorded by [11, 1] observed maximum landslide events on slope angles ranging from 10° – 20°, followed by slopes of 30 ^{0} – 40°. Study completed by [14] reveal landslide frequency reached a peak value at slope angles of 26° – 30° and recorded a sharp decline in frequency when slopes exceeded 45°.

Study conducted by [12] recognised a steady increase in debris slide with increase in slope angle with most slides occurring within the 35 – 45° class. They found a sharp decrease in frequency of occurrence on slopes above 45°, and this they attributed to the highly unstable nature of such slopes. Certainty Factor (CF) approach was adopted for landslide hazard analysis by [15], their result was similar to those of other authors as no event was recorded on slopes beyond the 50° class, rather, there was higher frequency of landslide occurrence in the 30 – 40° slope class, and between 40 – 50° slope classes. This reduction on slopes higher than 45° is likely as a result of the occurrence of more stable materials on slopes above 45°. Lending support to this, [16] concluded that on low to moderate slopes, the probability of shallow debris slide occurrence increases as the slope increases, however, as slope angles approach vertical, the potential for rock falls and topples increases.

Soil characteristics likely to influence landslide occurrence include its shear strength, degree of weathering, drainage potential, clay content, as well as thickness. Material susceptibility to failure is partly related to the soil's physical conditions, [10], soils with higher shear strengths have higher resistance to failure than soils with lesser shear strength. Certain factors can reduce the shear strength of a soil, e.g., increase in the degree of weathering [17], increase in water absorption and resulting swelling [10]. It has been suggested by [18] that landslide will occur when a threshold shear stress dependent on soil moisture and slope angle is exceeded. One can then say that soils with better drainage potential have lesser susceptibility to landslides than soils with poorer drainage potential. Weathering condition of the soil is very important for landslide evolution. Research conducted by [19] in the Mbale area of Uganda showed that one of the reasons for the high susceptibility of the study area to mass-movement is the presence of deeply weathered ferrallitic soils underlain by Tertiary and Pleistocene volcanic rocks. Some other authors e.g., [20-22] relate the occurrence of landslides directly with weathered soil materials. Apart from intensity of soil weathering, clay content is equally important in landslide analysis [23-25]. Type of clay mineral present in the soil is important in determining the susceptibility of the soil to landslide. Sensitive or quick clays as well as expansive clays (i.e., those that lose much of their strength upon remoulding at constant water content) are more often associated with mass-movement than non-quick clays [2].

2. METHODS

2.1 Data

Data used in this study include 31m digital elevation model, DEM, 1.5m Satellite Pour l'Observation de la Terre, SPOT 6 image of study area in three bands of red, green and blue, an exploratory soil map and agro-climatic zone map of Kenya (KSS map) on a scale of 1:1,000,000. Analysis of these data were completed with ArcGIS 10. Five event parameters likely to influence debris slide were adopted for this study.

2.2 Surface Derivatives

Information on slope angle, curvature and elevation can be derived from a DEM as done by [26]. The 31m DEM was used to produce two surface derivatives, slope and hillshade layers. Slope angle has been recognised as a major driver of slope instability for as slope angle increases, shear stress in soils or other unconsolidated materials increases, [27]. Hillshade layers enable map users visualise the relief of a study area in three dimensions. Slope and hillshade layers alongside the 1.5 m SPOT 6 image were used to visualise the shape of the landform and inform terrain mapping and identification of terrain units. Terrain of the study area was mapped in ArcGIS using polygons, which were referred to as terrain units (Fig. 2). These units have similar topographic features. All terrain units had unique attributes in ArcGIS, these were used in production of the final susceptibility map.

2.3 Numerical Rating Scheme

Some factors are thought to influence debris slide occurrence. They include extreme rainfall, slope angle, soil type, and earthquake, among others. These factors can be grouped into two, preparatory and triggering factors, [28]. This study focuses on preparatory factors like slope angle, soil drainage, proximity to drainage lines, and soil thickness. The Coulomb Equation of stability analysis was used to test the relationship between identified parameters capable of influencing shallow debris slide and the factor of safety. The concepts of factor of safety and justification for adopting the Coulomb Equation are explained.

2.3.1 Factor of safety

Slope stability is usually expressed in terms of a factor of safety, F, which is the mathematical relationship between resisting forces to slope failure and driving forces of slope failure, [29].

This is represented as,

$$F = \frac{\text{sum of resisting forces}}{\text{sum of driving forces}} \quad (1)$$

Where F is the factor of safety

When the value of $F < 1$, slope is likely to fail; when $F > 1$, slope is likely to be stable.

2.3.2 Coulomb Equation

Stability analysis for shallow debris slides can be computed using the Coulomb Equation [29,30] as represented in Equation (2),

$$F = \frac{c + (h\gamma \cos^2\beta - mh\gamma_w \cos^2 \beta) \tan\phi}{h\gamma \sin \beta \cos \beta} \quad (2)$$

Where

F = factor of safety
h = vertical thickness of the material above plane of failure (m)
γ = specific weight of the soil (kNm/3)
γ_w = specific weight of water (kNm/3)
β = slope angle (^{0})
m = height of the water table above plane of failure; expressed as a fraction of the vertical thickness of the material so that m = 1.0 if the water table is at ground surface and

m = 0 if the water table is at or below the plane of failure
c = cohesion
tanϕ = friction angle of material

Equation 2 was used to justify the accurate allocation of hazard ratings to parameters capable of influencing shallow debris slide. Equation 2 shows that modelled factor of safety was above 1 for all tested parameters. Relationships with factor of safety differed from one parameter to another, some had linear and others had non-linear relationships with factor of safety. This is reflected in the non-uniform attribution of weighted values to individual parameters on a scale of 0-5. Allocation of weighted hazard ratings to parameters was based on their individual relationships with factor of safety as well as expert judgement, as shown in subsequent sections. Similar attributions of weighted hazard ratings have been suggested in the literature [31]. Values of all variables in Equation 2 are shown in Table 1. These correspond to soils in the study.

Table 1. Variables used for calculating relationship between parameters and factor of safety

S/N	Variable	Value
1	h	0.01 – 1.8 m
2	γ	18 kNm/3
3	γ_w	9.81 kNm/3
4	β	0°- 30°
5	m	0 – 0.4
6	c	20
7	tanϕ	18 – 32

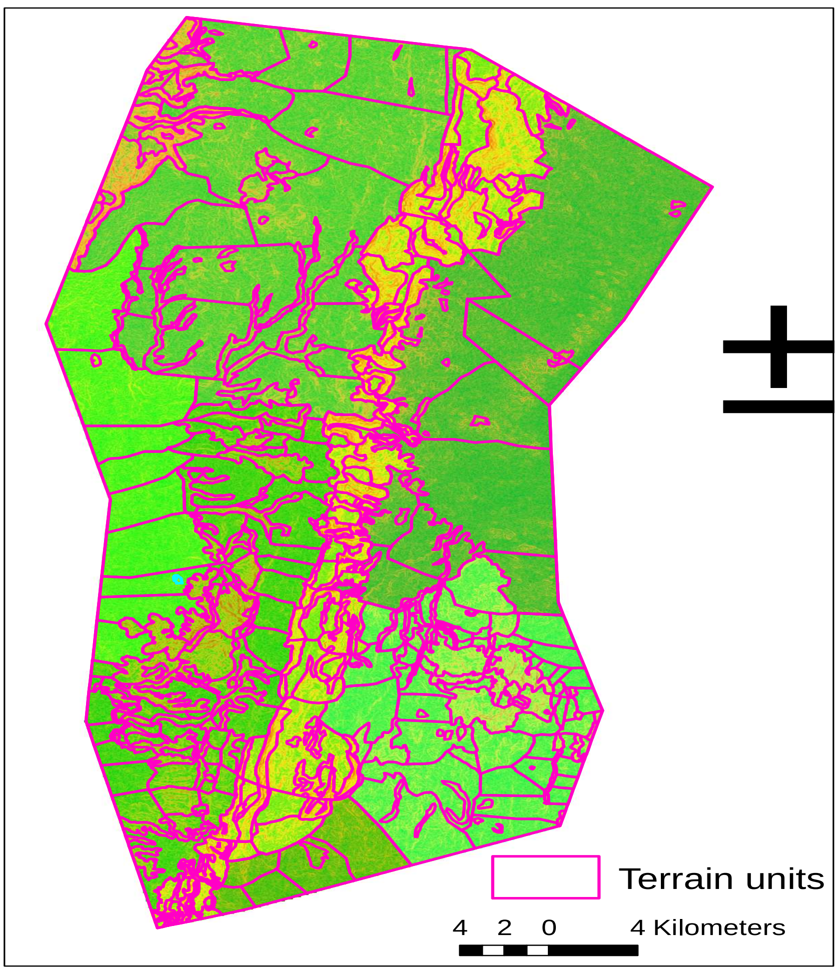

Fig. 2. Terrain units showing polygons with similar topographic features

2.3.3 Slope angle

Two slope values were calculated for this study, maximum slope and mean slope. The mean slope values ranged between 2.9° and 29.6° while the maximum angles were between 11.4° and 59°. Maximum slope values were not used as they skewed the resulting susceptibility map to show plains exhibiting slopes of 30+ degrees. This is due to the DEM recognising the maximum slope angles in the plains and using same across the entire polygon. By selecting the mean values this issue was eliminated and provided a more realistic and representative slope for each polygon. Relationship between slope and factor of safety was computed from Equation 2, it was found that the relationship between slope angle and factor of safety at tested angles was not linear. For example, factor of safety at 30° is three times less than the factor of safety at 10°, while factor of safety at 30° is half the factor of safety at 15°. The importance of this method is to justify the use of non-linear hazard ratings for slope as documented in Table 2.

Table 2. Mean slope hazard class for study area

S/N	Mean slope angle	Hazard rating
1	0 – 5	0
2	5 – 10	1.7
3	10 – 15	2.5
4	15 – 20	3.5
5	20 – 25	4
6	>25	5

Table 2 indicates that slopes angles greater than 25° had the highest hazard rating of 5 while angles of slope below 5° had minimal hazard rating of zero (0).

2.3.4 Soil type

Some soil types have been recognized as more susceptible to landslides than others, e.g., deeply weathered volcanic soils [21]. The soil type of the study area was derived from the KSS map. Three soil types were identified; Lithosols (Leptosols), Solonchak, Xerosol (Gypsisols). To test the strength of the soil types with the Coulomb Equation, shear strength of soil was used as a surrogate for soil type. Friction angles of the three soil types vary between 18° (min) and 32°(max). These soils are made up of clay, loam and sand of varying proportions, leptosols and gypsisols have higher proportions of clay while solonchak has a higher proportion of sand. In order to vary values of shear strength of the materials and test their relationship with the final model as produced, 18° was adopted for the leptosols and gypsisols due to their higher clay content (increase in clay content reduces shear strength in the soil - [24,25] while 32° was used for solonchak due to higher sand content. Based on this, a hazard rating of 3.5 is assigned to leptosols and gypsisols and a hazard rating of 2 is assigned to solonchak and 1 for bedrock. The hazard classification is premised on the fact that on a scale of 1 – 5, soils with lesser friction angles would have higher hazard ratings while soils with higher friction angles would have lesser hazard ratings, Table 3.

Table 3. Illustration of friction angles of soils and hazard rating

S/N	Friction angle	Hazard rating
1	$>41^0$	1
2	31^0 - 40^0	2
3	21^0 - 30^0	3
4	11^0 - 20^0	4
5	$<10^0$	5

Table 3 shows that soils whose friction angles are above 41° were assigned a hazard rating of 1 (minimal identified hazard). On the converse, friction angles less than 10° had the highest hazard rating of 5.

2.3.5 Soil drainage

Increase in soil moisture decreases soil cohesion [32], factor of safety is very sensitive to cohesion [29]. Soil drainage was obtained from classification of the KSS map. Three out of six soil drainage classes identified for the entire country of Kenya were present in the study area. They are moderately well drained, well drained and excessively well drained. The value of 'm' in Equation 2 was derived from the soil drainage classes where very poorly drained soils = 1.0, poorly drained = 0.8, imperfectly drained = 0.6, moderately well drained = 0.4, well drained = 0.2, and excessively drained = 0. Relationship between factor of safety and soil drainage as tested with Equation 2 is linear for all the soil drainage classes, hence the use of linear hazard rating in Table 4.

The implication of Table 4 is that well drained soils are thought to have lesser susceptibilities to debris slide while poorly drained soils are expected to have higher susceptibilities to debris slide. Thus, on a numerical weighting of 1 – 5, maximum hazard value is given to the worst drained soil and minimum hazard value assigned to the best drained soil.

Table 4. Soil drainage hazard rating

S/N	Soil drainage	Hazard rating
1	Very poorly drained	5
2	Poorly drained	4.2
3	Imperfectly drained	3.4
4	Moderately well drained	2.6
5	Well drained	1.8
6	Excessively drained	1

2.3.6 Proximity to drainage lines

It has been suggested that frequency of landslide occurrence in places with less than 50m proximity to drainage lines is six times greater than frequency of landslide occurrence in areas more than 200 m from drainage lines, [33]. This was attributed to the fact that terrain modification as a result of gully erosion may influence landslide initiation. Thus, a direct relationship between proximity to drainage lines and landslide frequency is established. Proximity to drainage was derived from the SPOT 6 image of study area. Based on this, the study area was divided into two, areas with drainage lines and areas without drainage lines, Fig. 3. Numerical hazard rating for proximity to drainage lines is presented in Table 5.

Table 5. Proximity to drainage lines

S/N	Proximity	Hazard rating
1	Presence of drainage lines	5
2	Absence of drainage lines	1

Areas with drainage lines were assigned a hazard rating of 5 and areas without drainage lines were given a hazard rating of 1, as shown in Table 5. This is based on study by [33] as already highlighted.

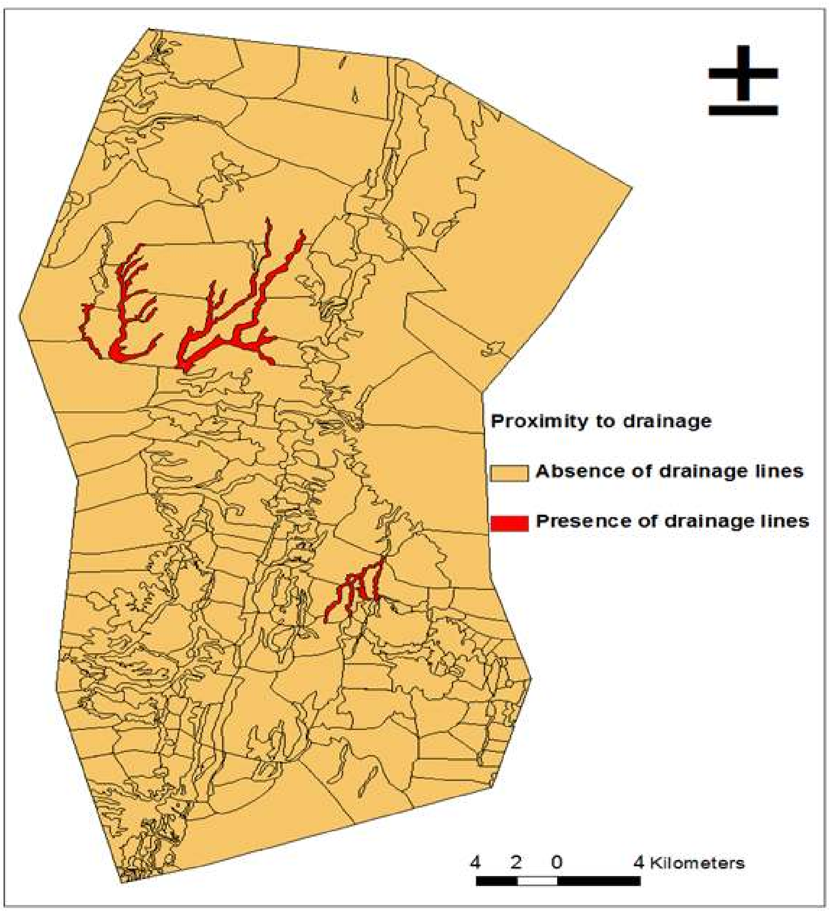

Fig. 3. Proximity to drainage map of study area

2.3.7 Soil thickness

Recognition of soil thickness as a parameter of interest in landslide studies has been proposed [34]. Soil thickness identified by the KSS map varies between 0.01 m – 1.8 m, this was used as a surrogate for 'h' in Equation 2. Four classes of soil thickness were present in the study area. They include Shallow, Shallow to moderately deep, Very deep and Surface. Relationship between soil thickness and factor of safety was tested with Equation 2. This revealed an inverse relationship. Factor of safety for tested soil thickness was not a linear distribution, hence, the use of non-linear hazard rating for soil thickness in Table 6.

Table 6. Soil thickness hazard rating

S/N	Soil thickness	Hazard rating
1	Extremely deep, >1.8 m	5
2	Very deep, 1.2 – 1.8 m	4
3	Deep, 0.8 – 1.2 m	3
4	Moderately deep, 0.5 – 0.8m	2.3
5	Shallow, 0.01 – 0.5 cm	1.5
6	Surface	0

Table 6 presents that areas with bedrock outcrop were assigned a hazard rating of zero (0) showing there is no debris in such places hence debris slide is not likely to occur. On the other hand, areas with deep soils were assigned higher hazard ratings in Table 6 because of the presence of thick materials which could fail in the event of reduction of factor of safety.

2.4 Production of Susceptibility Map

Susceptibility map was produced by multiplying all the parameters of interest. The product was divided by 130 as shown in equation (3). This division was made so as to return susceptibility values to a scale range of 0 – 5.

Susceptibility map = (Slope angle^2*Friction angle of soil*Soil drainage*Soil thickness*Proximity to drainage line) /130 (3)

Multiplication was favoured so as to ensure that areas with slope or soil thickness hazard rating of zero (0) had susceptibility values of zero in the final susceptibility map. This is because where the slope is too gentle to initiate failure, materials are not likely to fail and where there is no material to fail, debris slide is not likely to occur. The square of slope hazard rating was used in Equation 2 to ensure slope had a higher hazard rating over the other parameters. This is because despite the thickness of the material, or intensity of stream undercutting, landslide is not likely to occur until a critical angle is exceeded. This critical angle depends mainly on slope, [10].

3. RESULTS AND DISCUSSION

A major challenge faced in this work is the lack of field validation inventory. Susceptibility map Fig. 4, was classified into six classes, minimal (0), very low (0 – 1), low (1 – 2), moderately low (2 – 3), high (3 – 4) and higher (4 – 5). The map shows that areas with drainage lines had the highest susceptibility values, 3 – 5. With the use of the square of slope hazard rating for this project, (slope^2), polygons with steeper slope angles, have higher susceptibility values than polygons with lower slope angles. The highest susceptibility values identified from the map apart from areas with drainage lines range from 1 – 2 (low susceptibility class) and this is found in polygons around the western scarp of the KRV. Rift floor and areas with bedrock outcrop such as the volcano (Fig. 1) had the least susceptibility values of zero (0), thus, they have minimal susceptibility to debris slide. Fig. 4 suggests that polygons with lesser clay content such as solonchak, have lesser susceptibility to debris slide than those with higher clay content e.g., leptosol. This would be expected because frictional resistance decreases with increase in clay content, and thus, leptosol and gypsisol with higher clay content could be preparatory soils in debris slides occurrence, especially after heavy rainfall [23-25,33,35,36].

The influence of soil drainage is not properly felt in the final susceptibility map, and this is because despite the height of ground water, debris slide is likely to occur when a critical angle is exceeded and when there is active toe undercutting. This is illustrated in the final map where well-drained are more susceptible to debris slide than the moderately-well-drained soils. The Coulomb Equation suggests there should be a higher susceptibility of debris slide in deeper soils than in shallower soils. Minimal hazard value (0) of polygons around the volcano upholds the relationship between the Coulomb equation and factor of safety. Bedrock outcrop on volcano indicates there is no material to fail despite having higher slope angles and therefore, there is minimal susceptibility to debris slide on that area. Fig. 4 illustrates that polygons with close proximity to drainage lines had highest

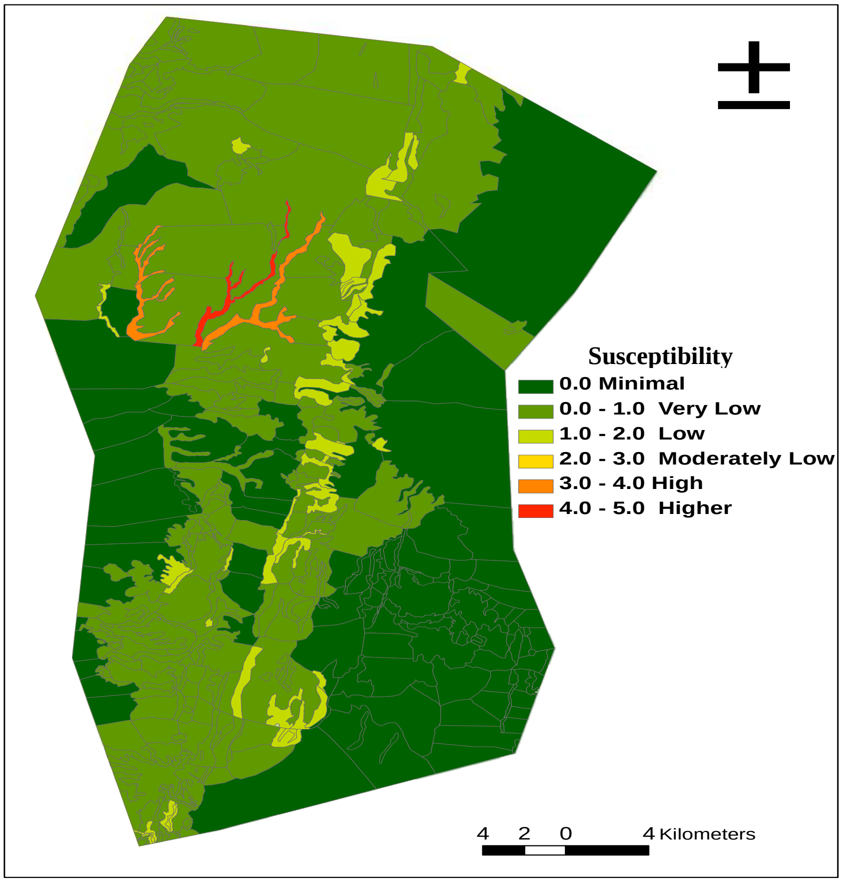

Fig. 4. Debris slide susceptibility map showing six susceptibility classes

susceptibility values (3 – 5) to debris slide. A similar trend was identified by [33] in Hong Kong where the frequency of landslide occurrence in places with less than 50 m proximity to drainage lines was six times greater than the frequency of landslide occurrence in areas more than 200 m from drainage lines. Despite being a semi-arid environment, occasional heavy rainfalls may influence debris slide initiation [37].

3.1 Discussion

The Coulomb equation adopted for this study was used to justify accurate allocation of hazard ratings to parameters capable of influencing shallow debris slide occurrence. The only parameter not tested with this equation was proximity to drainage. For this, a surrogate was derived from published literature. Fig. 4 shows that proximity to drainage lines was the single most important parameter likely to influence debris slide in the study area. This is significant as active toe undercutting resulting from actions of running water is expected to reduce stability, and thus, encourage failure of materials. It is not a surprise therefore that the final susceptibility value of areas close to drainage channels was greater than all other values on the susceptibility map (3 – 4). The susceptibility of other polygons despite their individual hazard classes range from (0 – 2). This indicates that the study area is not under immediate threat of debris slide except in the case of a forcing event such as seismic events. In such an instant, areas with higher slope values and active toe undercutting are expected to be more susceptible to debris slide than areas with lower slope angles and shallow soils. It should be noted however that as slope angles approach vertical, probability of shallow debris slide occurrence reduces and the potential for topples and rock-fall increases [16].

3.2 Uncertainties and Recommendations

Uncertainties are central features of geotechnical and geological engineering [38]. The major uncertainty of this project is the absence of landslide data in the study area to validate the susceptibility map as produced. Event controlling parameters used in this project have been selected based on literature review as no field work was carried out for this study. All data used here except soil map were derived from remotely sensed sources. This project has therefore developed a method that can be used to assess debris slide susceptibility in areas; without landslide data, locations with inaccessible terrain or where ground truthing has not been undertaken or is unfeasible. It could equally be adopted in an area with landslide inventory thereby validating or modifying the method. Other parameters like seismic data, rainfall data not included in this project could be incorporated in the adoption of this method in an environment with rich data, this will improve quality of the final susceptibility maps and lead to a better understanding of debris slide susceptibility of an area. The development of landslide inventory will be very ideal in testing this method as this will enable the researcher modify or validate their final susceptibility map. Secondly, fieldwork where practicable is also needed so as to have a physical review of terrain of an area in the adoption of this method. Finally, a more detailed polygon mapping with a higher resolution DEM could be carried out, this would improve quality of maps produced.

4. CONCLUSIONS

Utilizing Turkana region of Kenya as a test area, a numerical method of mapping debris slide susceptibility has been presented. This involved identification of five key parameters thought to influence occurrence of debris slide; slope angle, soil drainage, soil depth, proximity to drainage channel and friction angle of soil. A couple of methods have been suggested for landslide susceptibility mapping [e.g., 3], but use of the Coulomb Equation of stability analysis for justification of hazard ratings of selected parameters has not always been adopted. This study adopted the Coulomb Equation as a mathematical paradigm for attaching hazard ratings to event controlling parameters. Remotely sensed data, a soil and agro-climatic map of the study area were used for analysis in ArcGIS. Thematic layers of the five controlling parameters were made and hazard ratings attached to them.

Final susceptibility map indicates that proximity to drainage channel and slope angle are very strong parameters of interest in debris slide susceptibility assessment and mapping. In a seismically active region such as Turkana, the five event controlling parameters identified in this study are not the only factors capable of influencing shallow debris slide occurrence. Faults and earthquake hazard assessment could be incorporated to improve the quality of geohazard assessment for the area. Fieldwork was not undertaken in the course of this study and hence, susceptibility map could not be verified. This study has presented a method for; regional debris slide susceptibility study, susceptibility mapping in a terrain with no landslide data and a difficult terrain with little accessibility. The next logical step towards enriching this study would be the inclusion of other identified geohazards (such as faulting and seismic hazard) in the model as well as susceptibility map validation in an area with landslide data.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

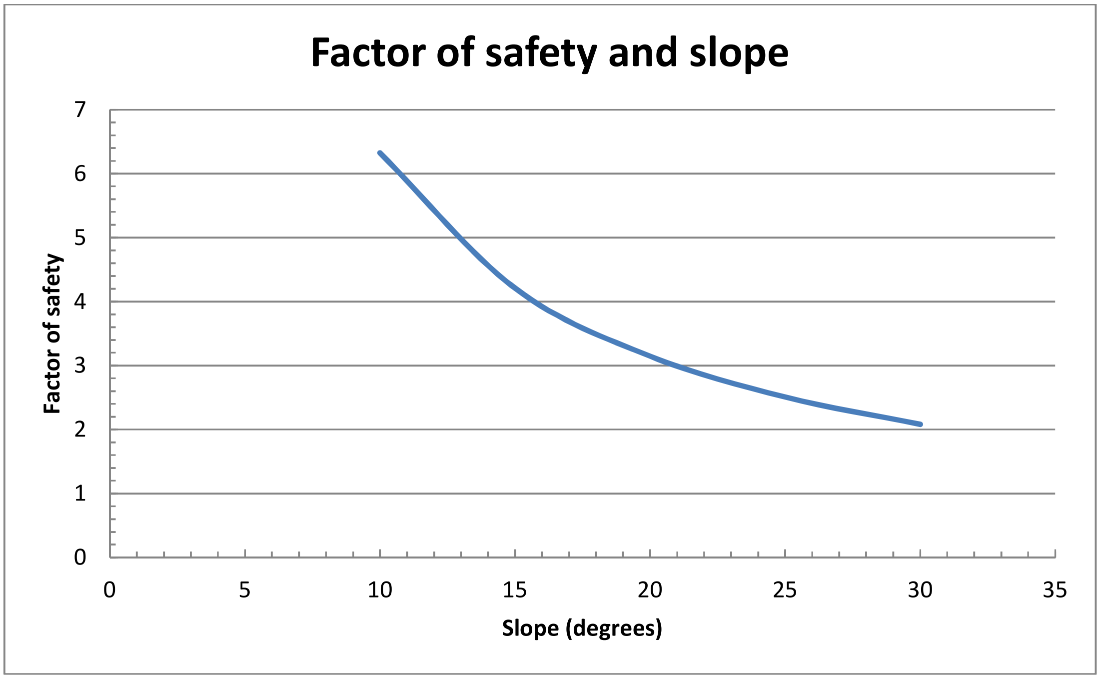

Fig. 1. Relationship between factor of safety and slope angle

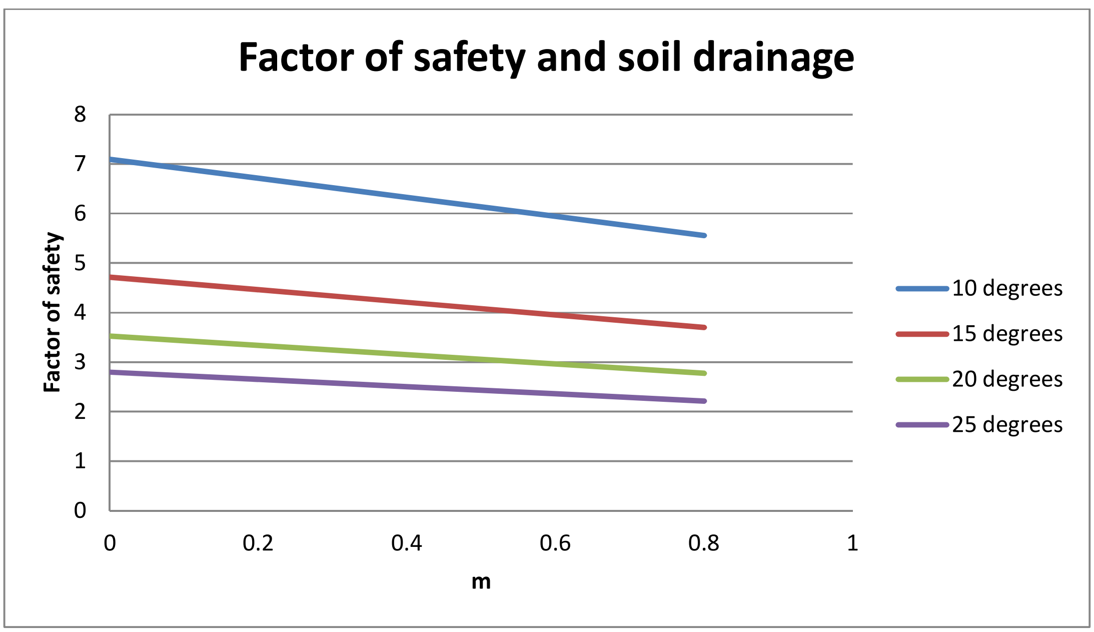

Fig. 2. Linear relationship for factor of safety and soil drainage across slope angles of 10°, 15°, 20° and 25°

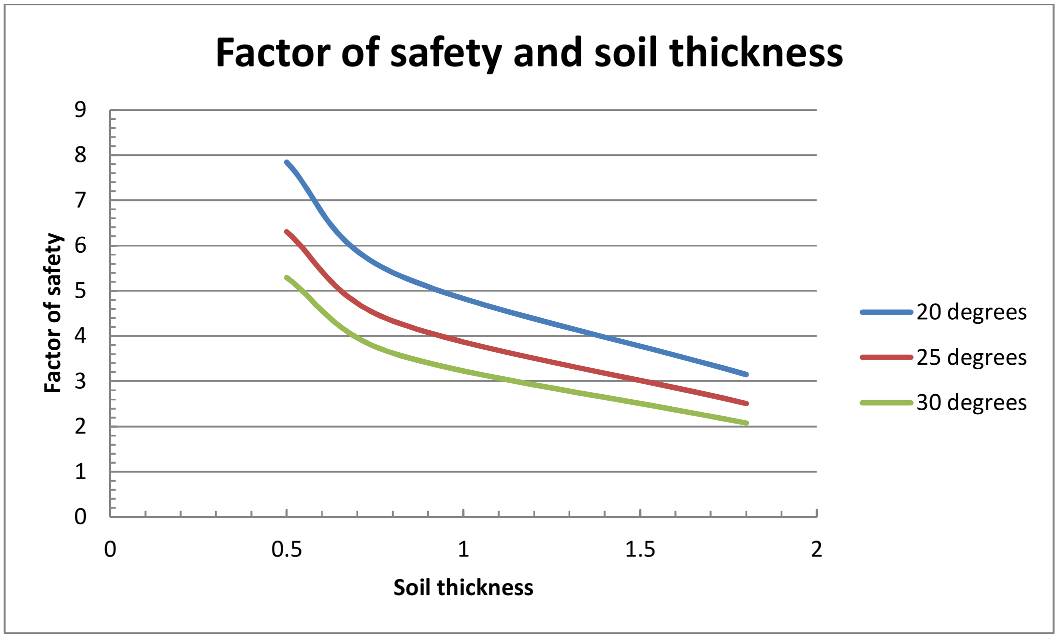

Fig. 3. Relationship between soil thickness and factor of safety at 20°, 25° and 30° slopes

Table 1. Relationship between soil thickness and factor of safety

Soil thickness	Factor of safety at various slope angles				
	10°	**15°**	**20°**	**25°**	**30°**
0.5m	15.56852731	10.40966589	7.839892	6.3061344	5.290807319
0.8m	10.76955191	7.189913131	5.4033883	4.334299748	3.624140652
1.8m	6.326056167	4.208660581	3.1473664	2.508526921	2.080930775

Table 2. Relationship between soil drainage and factor of safety

Soil drainage	Factor of safety at various slope angles				
	10°	**15°**	**20°**	**25°**	**30°**
0.8	14.79597669	9.901280256	7.465626	6.0140064	5.054865
0.6	15.182252	10.15547307	7.652759	6.1600704	5.172836
0.4	15.56852731	10.40966589	7.839892	6.3061344	5.290807
0.2	15.95480262	10.6638587	8.027025	6.4521984	5.408779
0	16.34107794	10.91805151	8.214158	6.5982624	5.52675

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