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An Application of CAMEL to Assess the Occurence of Earthquake Induced Landslides

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Abstract

Earthquakes are among the principal triggering factors of landslides. Triggering of landslides revolves around two main classes of parameters: (i) the earthquake parameters (magnitude, peak ground acceleration or Arias intensity, epicentral and rupture dynamics), and (ii) the site parameters (geology, tectonic setting and topography). However, in most cases landslides data is not available after the earthquake as the attention is given to primary damages of the earthquake. The development was not different after the 2009 Karonga earthquake which recorded a 6.0 Magnitude. In this respect, a quasi-quantitative approach was used to draw inference on the possibility of occurence of landslides after the Karonga earthquake by applying the knowledged gained from the documented worldwide landslides inducing earthquakes and applying Comprehensive Areal Model of Earthquake (CAMEL) and Geographic Information System (GIS) programs using the possibility module of CAMEL embedded in GIS.. It emerged that the possibility of occurrence of earthquake induced landslides was fairly below par for the Karonga earthquake. The key influencing factors being the geomorphology and the geology of the area and the fault type on which the earthquake occurred.

Keywords: Comprehensive Areal Model of Earthquake; Degree of Support; Earthquake Induced Landslides; Earthquake Magnitude; Fuzzy Logic; Karonga

Introduction

Earthquakes are inavitableannihilating geological events on Earth. Adding to the destruction of structures and properties worthy billions of money, earthquakes can induce different forms of ground rupture and instability in the ground which include: ground displacement with tectonic uplifting or subsidence of vast areas and lateral movements, the formation of devastating seismic sea waves culminating from the sudden vertical movement of the sea bed, liquefaction of unconsolidated water saturated deposits and mass movement (Anderson & Richards, 1989). Karonga is situated in the Northern part of Malawi with geographical coordinates; 11° 22' 0" South, 34°10' 0" East. The area is within the Malawi Rift System, (MRS) which forms part of the East African Rift System (EARS) (Figure 1). EARShas attracted the interest of the geoscientists around the globe who are craving to fully comprehend the rifting process and the likely consequences. The geological setting of Karonga exposes it to natural hazards such as earthquakes and landslides along the faulted margins in response to ground shaking. Msilimba [1]have documented a number of landslides in the Northern part of Malawi, partculary in Mzimba area contiguous to Karonga. The focus of their studies has been on rainfall and anthropogenic activities as landslides triggering factors. However, the location of Karonga within the EARS, as shown in (Figure 1), vividly suggests that the area is potentially exposed to seismic activities that may induce landslides. Thus, this study is aimed at assessing the feasibility of occurrence of landslides during and/or after the 2009 earthquake that affected Karonga and contiguous districts like Chitipa and Mzimba.

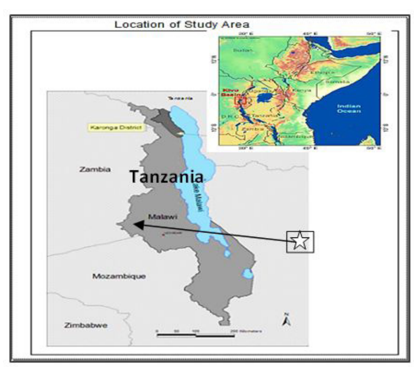

Figure 1: Location of study area (Extracted from Google Maps and replotted in ArcGIS). The insert shows the EARS.

Geology of the Study Area

Karonga is predominantly underlain by Precambrian to Lower Palaeozoic metamorphic and igneous rocks that make up the basement complex of Malawi. Uncomfortably overlying the basement complex are several patches of the Karoo sediments and Cretaceous to Recent sediments such as lacustrine and fluvial sediments[2]. The basement complex is dominated by gneisses (biotite and amphibolites gneisses, (Figure 2) and granitic intrusions of Umbendian tectonic domain that extends from Southern Tanzania to Malawi. The Karoo sandstone and shales with coal seams, which are assigned relative dates of the Upper Carboniferous to Triassic period, were deposited in basin greatly controlled by faults characterised by N-S and NW-SE trends (Ray, 1975). Cretaceous to Pleistocene Lacustrine sediments lay unconformable to the basement complex gneisses. The lacustrine sediments include: Dinosaur, Chiwondo, Chitimwe, Mwesia and Sungwa beds (Figure 2). The lakeshore plain is predominantly covered by beach sands, alluvium and marsh deposits of Upper Pleistocene to recent age.

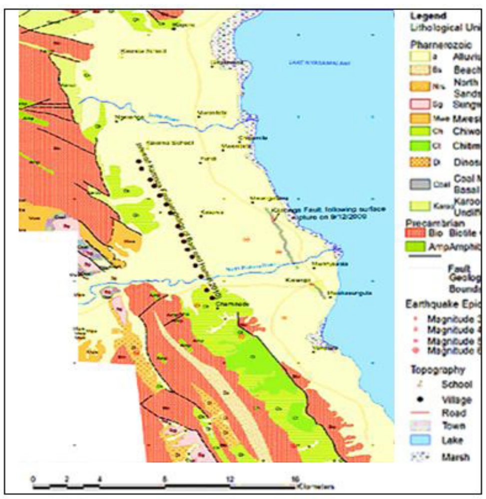

Figure 2: Geological Map of the study area (Karonga area) showing litho logical units and associated faults in the area. The Karonga fault that caused the December 2009 earthquake is also shown in red as a thick line on the eastern side [2].

Seism tectonic Setting

Karonga lies within the MRS which forms the southern part of EARS. The EARS extends from the Red Sea/Gulf of Aden to Malawi and it is seismically active beyond. [3], who applied the GPS-derived model, found that EARS has extension rates are 3.7-3.8 mm/yr. Further, [3], established that the southern East African Rift (SEAR) has an has a remarkably large seismogenic thickness of 35-40 km, which is apparently responsible for tilted basins and very long faults with potential for 7-8 magnitude normal-faulting earthquakes (Figure 3). It was not surprising that from 6th- 8th December 2009, swallow earthquake sequence (Mw > 5.5) hit the Karonga area of Northern Lake Malawi (Table 1). The main shock (Mw 6.0) was preceded by foreshocks with magnitudes 5.8, 5.9 and 5.4. The epicentre situated 50 km west of the rift-bounding Livingstone Fault, within the hanging-wall (Figure 3).

Aside the four large earthquakes, [4] discovered that a swarm of 29 small earthquakes (Mw ≥ 4), nine of which were larger than body-wave magnitude (Mb = 5), occurred[3] made efforts to model the seismic behaviour for the largest 4 earthquakes (the 6th, 8th, 12th and 19th December). The modelling also revealed a normal-faulting mechanism with a depth of 20 km whose orientation and location were consistent with rupture of small patch of the Livingstone Fault. A study by [2] concurs with the findings of [3]on fault type. [2],the Karonga fault, is a normal fault which trends N290-N350 and close to the surface it dips at higher angles due West.

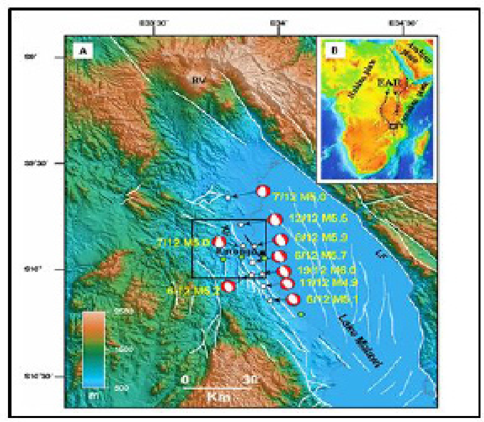

Figure 3: The tectonic setting of the study area (Karonga). The insert shows the EARS. And the landsat image of northern Lake Malawi with focal mechanisms of the 2009 Karonga earthquakes [4]. KF represent Karonga Fault and LF stands for Livingstone fault.

Date	Magnitude (Mw)	Latitude	Longitude	Depth	Fatalities
6/12/2009	5.8	10.16°S	33.82°E	10 km	
8/12/2009	5.9	9.948°S	33.878°E	8 km	1
12/12/2009	5.4	9.96°S	33.88°E	10 km	
19/12/09	6	10.108°S	33.84°E	6 km	3

Table1: List of the earthquakes that occurred in Karonga 2009 [3].

Earthquake Damage

The Malawi Government declared the Karonga earthquake a National Disaster on 21st December and the area was described as a seismically dangeous area [2,4] reported that over 1000 houses collapsed, a further 2900 were damaged, 300 people were wounded, and 4 were killed. The earthquake was also characterised by rift structures and ground fractures in this region (Figure 4).

Figure 4: The damage experienced during the 2009 Karonga earthquakes [4]. (a&b) Show Surface rupture after the 2009 earthquake. (c) Road parting due to the impact of rupturing and (d) collapsing building due to series of earthquakes in 2009.

Methodology

Work undertaken to achieve the study objective involved obtaining a Digital Elevation Model (DEM) Map, reviewing extensively the literature on earthquake induced landslides and applying CAMEL program which is embedded in GIS to assess possibility of landslides occurrence.Reviewed sources include; scientific and technical papers, technical reports, seismological and landslides data by USGS and university theses. Valuable data was also obtained from internet sites and relevant books on EI landslides.A Digital Elevation Model (DEM) Map for Karonga was extracted from Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) Version 2(V2).The DEM has a 30 x 30-meter resolution.GIS was applied to analyse the DEM in order to calculate slope angle, aspect and curvature.

Approach

There are different approaches for landslides susceptibility analysis that have been propounded and implemented. The approaches may be distinguished into two main classes: qualitative and quantitative approaches. The hazard levels for the qualitative approaches are somewhat subjectively presented by descriptive terms based on expert opinion. Yalcinexplains that the most common types of qualitative methods merely use landslides inventories to identify sites of similar geological and geomorphological properties that are susceptible to failure but some qualitative approaches may incorporate the concept of ranking and weighing, and may evolve to be semi-quantitative in nature. Thus, the predictive power of the approaches varies in the weights of the parameters. However, weights evaluated by the experts are highly personal and may contain a degree of virtual admission. Quantitative approaches on the other hand, minimise the personality and bias in the weight assessment processes and analyse the relationship between landslides occurrence and its dependency on environmental factors more objectively. The quantitative approaches fall into two categories: deterministic and statistical methods. According to [5], deterministic methods analyse the slope stability using physical based models and are slope stability using physically based models and are expressed by the FS. However, deterministic methods are limited for predicting potential landslides on a regional scale because of the need for more detailed geotechnical data.Statistical approaches are applied to analyse landslides-controlling factors associated with landslides occurrence and rank the factors by using some statistical models.Yalcin discussed bivariate statistical analysis which deals with one dependent variable (in this case the occurrence of landslides) and one independent variable and the significance of each factor is analysed separately and combined with the landslide distribution Map, then weighting values based on landslide densities are calculated for each parameter class. The author father mentions that Statistical approaches have recently become common for evaluating landslide.

In this study a quasi-quantitative approach using fuzzy logic embedded in CAMEL are applied. CAMEL is a new, regional computer model for EI landslides hazards developed by Scot Miles and David Keefer using fuzzy logic systems, a component of the computing with words (CW) methodology. The objective of CAMEL is to deal with some of the current limitations in other EI landslides hazard models and create hazard maps that are more detailed and useful regulatory decision making [6,7].

CAMEL Design

CAMEL was designed and implemented as a fuzzy logic system[8]. Fuzzy logic systems are a subset of CW, which refer to a large body of methods and frameworks and numerically representing natural language for the purpose of characterising uncertainty and propagating it using some calculus of logic. According to [7],fuzzy sets can be thought of as a concept expressing a degree of belonging ranging from zero (0) and one (1). Basically, zero denotes certain not belonging and one denotes certain belonging. Fuzzy logic system refer to a configuration of IF-THEN rules that relate fuzzy sets of one or many input variable to fuzzy sets of one or more output variables.

CAMEL consists of two modules; the possibility and hazard module each of which are made up of numerous fuzzy IF-THEN rule-blocks [6].

The modules distinguish possibility-referred to as "Indicators"-from the knowledge about relative hazard-referred to as - "Intensifiers"-for each landslide type (Figure 5). According to the developers [6,8], the possibility module determines whether the occurrence of each respective landslide type is feasible and it applies landscape attributes while the hazard module determines the relative hazard, expressed as a real landslide concentration, for each possible landslides type. This study adopts the possibility module to determine the feasibility of occurrence of landslides after the 1949 (Mw 7.0) İzmir-Karaburun earthquake.

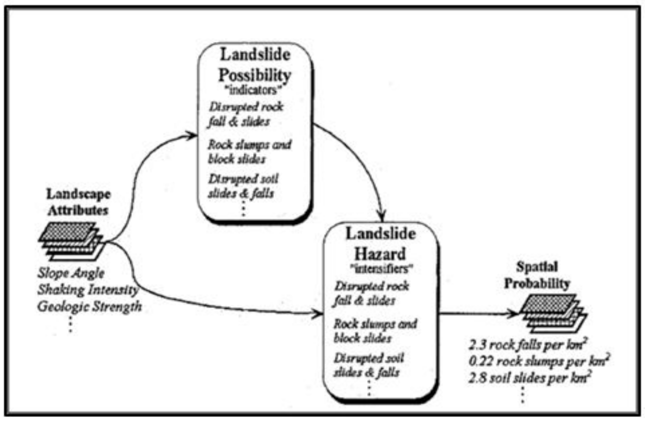

Figure 5: The two-module framework of CAMEL; the possibility and hazard modules [8].

The structure and data flow of the possibility module is given in (Figure 6). According to [7] the possibility module comprises of seven input variables, together with seven corresponding rule blocks that are recognised in series.

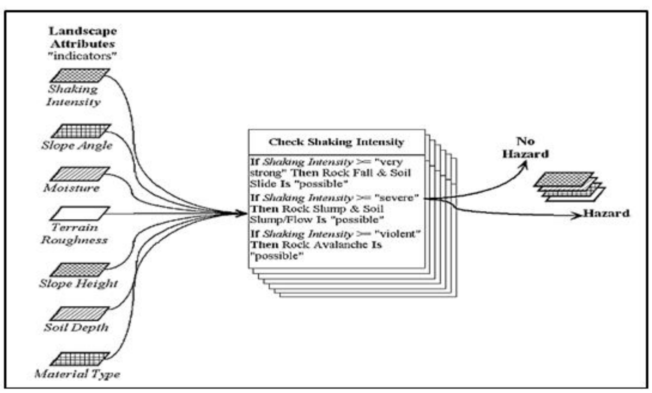

Figure 6: Design of the possibility module of CAMEL [8].

Each rule block consists of rules associated with a particular variable to collectively determine the degree to which each landslide type is possible. If one indicator variable specifies that a certain landslide type is not possible, the overall results of this chain of rule-blocks will be that landslide type is impossible. If one indicator variable specifies that a particular landslide type is not possible, the overall result of this chain of rule-blocks will be that the particular landslide type is impossible. If all variables show that a landslide type is possible, the minimum truth-value across these rule blocks is the output truth-value for the possibility module.

Furthermore, the developers explain that when the magnitude of the output truth-value indicates the degree to which the user-supplied input data suggests that each landslide type is possible based on the knowledge presented by the IF-THEN rules of the module. The AND operator is used for all rule blocks in the possibility module. Thus, the possibility design implies that CAMEL presumes landslide type is possible in the face of uncertainty[8] add that all rules in the possibility module are assigned an equal Degree of Support (DoS) weight of 1.0 and each landslide type is expressed through variable. If a truth-value is zero (0) for a particular landslide type that type is regarded to be impossible based on the inputs provided to CAMEL. Positive possibility values then denote that the particular landslide type is possible to the degree indicated.

The possibility module of CAMEL comprises of inputs as indicator variables. The variables are defined with the quantitative units, the domain, and the number and label of the fuzzy values for each variable. Miles and Keefer also clarify that, variables that have a domain defined by a minimum value of -1 have an actual minimum of 0 where the negative value is a designed technique to track whether the user has provided input value. For negative variables, “Missing” (data) is a valid data value. The design and specification of each indicator variable and associated rule block is described in Table 2 after [8].

Variable Name	**Units**	**Min**	**Max**	**Fuzzy Variable Labels**
P Terrain-Rough	Slope of slope angle	0	40	planar
				rough
P ShapeIn-tensity	Shake map intensity (MMI)	-1	12	missing_than_7
				greater_than_8
				greater_than_9
P SoilDepth	Meters	-1	10	missing
				shallow
				deep
pSlope-Hieght	Meters	-1	300	missing
				low
				height
P Material-Type	(linguistic)	-	-	missing
				rock
				soil
P Moisture	Percent	0	100	more_than_moist
				about_saturated

P Slope-Angle	Degrees from the horizontal	0	90	between_5 and 40
				between_15 and 40
				greater_than5
				greater_than_15
				greater_than_25
				greater_than_35

Table 2: CAMEL Possibility Module Input Variables [8].

Results

The EARS is characterised by natural hazards such as earthquakes, volcanic eruptions and landslides along the fault margins in response to ground shaking [2]. The most recent devastating earthquake in the Eastern and Southern Africa regions is the Karonga earthquake in Malawi which took place on 19th December, 2009 with a magnitude of Mw 6.0. After the 2009 Karonga earthquake only the geotechnical aspect and damage of the earthquake were analysed by seismological and geological experts in the area. There was no attempt undertaken to investigate if the earthquake had induced landslides. This implies that no information or documentation on landslides is available. From this background, the study also made an attempt to assess the possibility of the occurrence of landslides after the 2009 Karonga earthquake. To accomplish this objective through the application of ArcGIS and CAMEL, the following parameters were taken into account: Slope Height, slope angle, terrain roughness, material type, soil depth, moisture and shake intensity. The four topographical parameters; elevation, slope angle, slope aspect and slope curvature were used for correlation with susceptibility of landslide occurrence. The topographic parameters: Slope height, slope angle, slope aspect, and slope curvature were extracted from the Karonga DEM at 30 m×30 m resolution which was obtained from ASTER GDEM V2and downloaded from http://gdex.cr.usgs.gov/gdex/.To extract the weights for topographic parameters, the Karonga DEM was run in CAMEL which is embeded in Arc GIS (Figure 7).

Slope Height

Slope height was directly calculated from the Karonga DEM in ArcGIS through the Spatial Analyst Tools “Surface Analysis”. Before running the slope height layer, a fill command in Spatial Analyst Tools “Hydrology” was run to correct surface irregularities. After calculating the slope height, I reclassified the slope height at intervals of 500m (Figure 8). As noted in the literature review, slope heights between 750m and 1500m have high susceptibility of landslide occurrence in an event of a strong ground shaking. From (Figure 8), it shows that the epicentre of the earthquakes lie in the 500-1000 m category.

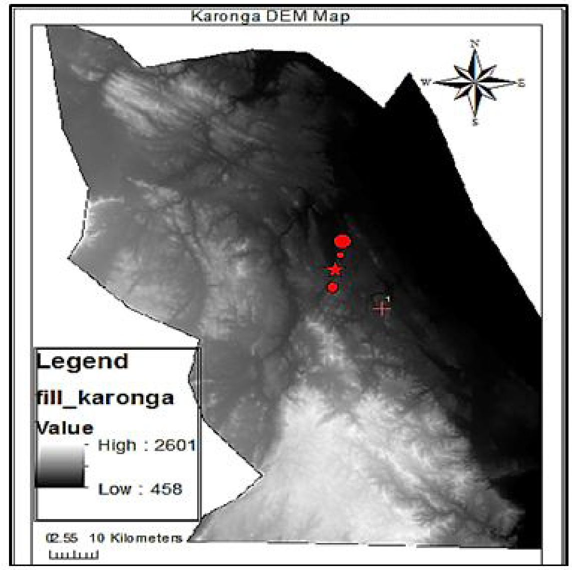

Figure 7: Digital elevation model for Karonga (The star is the epicenter of the Karonga main shock and the dots represent foreshock and the size is with respect to magnitude).

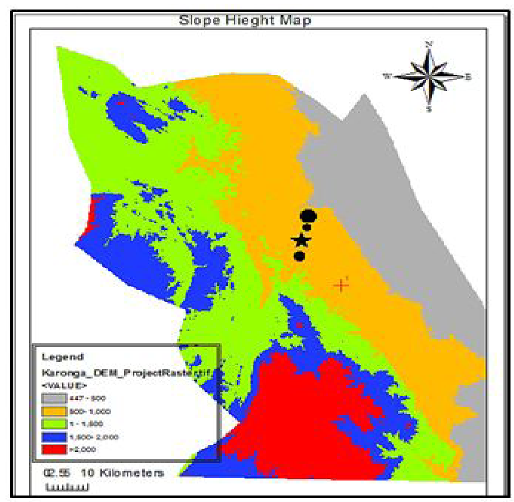

Figure 8: Slope height map derived from the Karonga DEM (The star represents the epicenter of the main earthquake and the dots represent the foreshocks-the bigger the dot the higher the magnitude).

To assess the influence of the slope height variable, the layer of slope height was then run in CAMEL integrated in ArcGIS to test for the variable’s fuzzy membership. The fuzzy membership was attained by running the slope height layer calculated from the Karonga DEM in ArcGIS through the Spatial Analyst Tools using ‘Surface Analysis’ (Figure 9). It can be observed that the epicentre of the Karonga earthquake lies in the slope membership value of around 0.4. This implies a low probability of the variable to cause landslides.

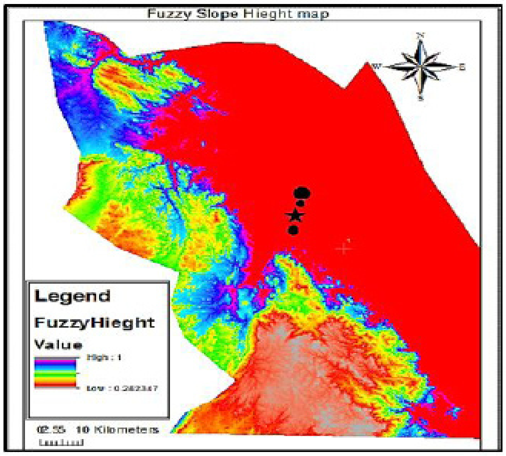

Figure 9: Slope height Map derived from the Karonga DEM (The star represents the epicenter of the main earthquake and the dots represent the foreshocks – the bigger the dot the higher the magnitude).

Slope Angle

The slope angle was directly calculated from the Karonga DEM in ArcGIS through the Spatial Analyst Tools “Surface Analysis”. Then reclassification was done for slope angle at intervals of 10°. From the possibility module rule block expressing knowledge about pSlopeAngle developed by [8]shown in Figure 10, the susceptibility values generally increase with the slope angle, but slopes exceeding 35° (classes 8-13) are more susceptible to landsliding. It can be noted from the slope angle Map that categories 10-20°, 20-30°, 30-40° and 40-50° are common.

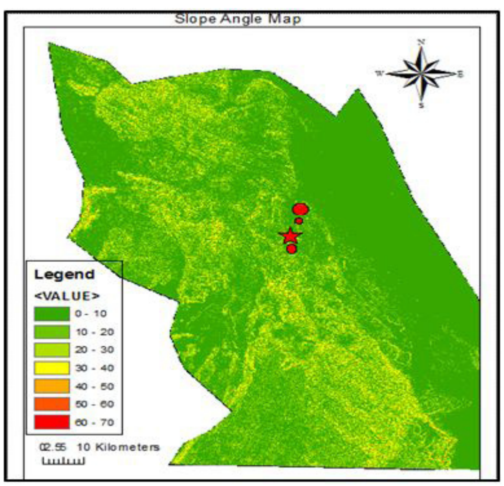

Figure 10: Slope angle Map derived from the Karonga DEM (The star is the epicenter of the Karonga main shock and the dots represent foreshock and the size is with respect to magnitude).

After computing slope angle from the Karonga DEM in ArcGIS through the Spatial Analyst Tools using ‘Surface Analysis’, the layer of slope angle was then run in CAMEL incorporated in ArcGIS to test for its fuzzy membership. It can be observed that the epicentre of the Karaburun earthquake lies in the slope membership value 0.2-0.6 (Figure 11).

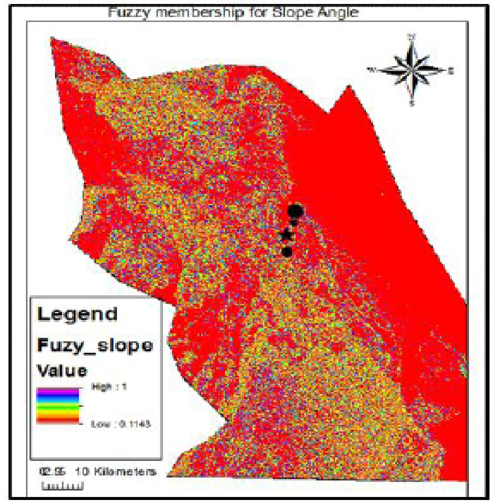

Figure 11: Fuzzy slope angle Map derived from the Karonga DEM (The star is the epicenter of the Karonga main shock and the dots represent foreshock and the size is with respect to magnitude).

Slope Aspect

Slope aspect values were also calculated from the Karonga DEM in ArcGIS through the Spatial Analyst Tools “Surface Analysis”. The slope aspect was separated into nine classes for the study, including flat, N, NE, E, SE, S, SW, W, and NW as presented in (Figure 12).

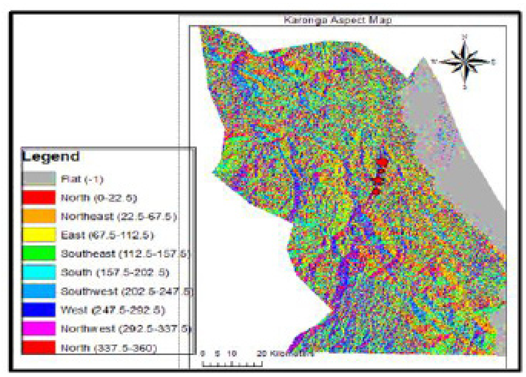

Figure 12: Aspect Map of Karonga(The star is the epicenter of the Karonga main shock and the dots represent foreshock and the size is with respect to magnitude).

From slope aspect layer, a fuzzy membership of slope aspect was extract in order to relate probability of occurrence of EI landslides with respect to slope orientation. The fuzzy slope aspect values were obtained after running the calculated slope aspect values which were calculated from the Karonga DEM in ArcGIS through the Spatial Analyst Tools “Surface Analysis”. (Figure 13) presents a Map of the fuzzy membership of aspect.

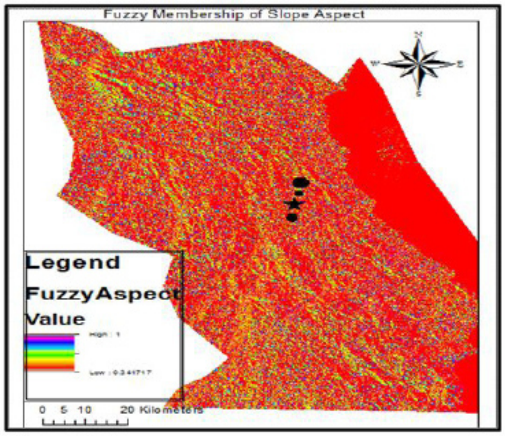

Figure 13: Fuzzy slope aspect map of Karonga (The star is the epicenter of the Karonga main shock and the dots represent foreshock and the size is with respect to magnitude).

Terrain Roughness

The terrain roughness is the second derivative of elevation in the down-slope-direction, with calculations done in degrees. The terrain roughness layer is attained by merely rerunning the surface analyst under the spatial analyst tool on the slope angle. It can be observed from (Figure 14) that the terrain roughness values are confined in the range of -2-0 and 0-2. The Terrain roughness Map indicates dominance of positive curvatures representing more convex surfaces than concave surfaces which are represented by negative values.

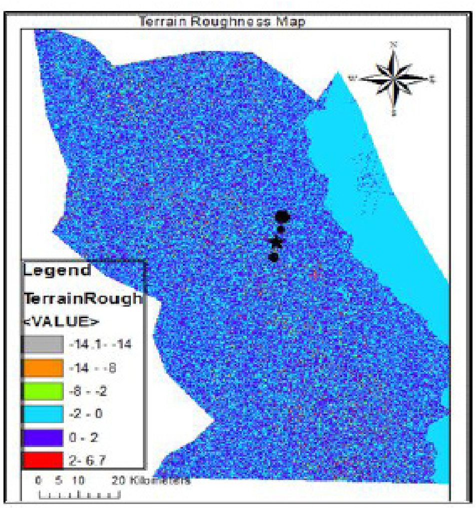

Figure 14: Terrain roughness calculated from the Karonga DEM (The star is the epicenter of the Karonga main shock and the dots represent foreshocks and the size is with respect to magnitude).

After calculating the terrain roughness, a fuzzy membership was derived from terrain roughness layer which was calculated in ArcGIS. The terrain roughness layer was calculated from the slope angle extracted from the Karonga DEM using Spatial Analyst Tools. A presentation of terrain roughness using fuzzy membership is given in (Figure 15). The membership values indicate a probability of 0.2-0.6.

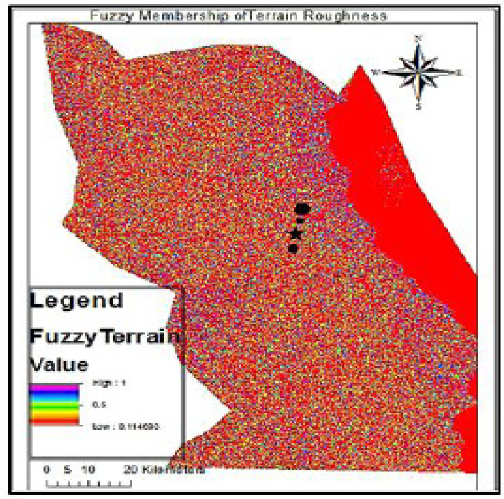

Figure 15: Fuzzy membership of Terrain roughness calculated from the Karonga DEM (The star is the epicenter of the Karonga main shock and the dots represent foreshocks and the size is with respect to magnitude).

Material Type

As indicated earlier in this study, CAMEL utilises qualitative interpretations of geologic materials when determining the locations and susceptibility of EI landslides. Unlike the aforementioned layers, which were derived using ArcGIS from a base DEM, the material type layer is created using knowledge and interpretation of the formations, assemblages and general distribution of lithologies. The material type value is selected from the predetermined a scale between 1 and 5 developed by Miles and Keefer. One (1) indicates the strongest material and five (5) the weakest(Figure 16). For instance, the "Strongest" material would be intact, cohesive, unweathered granite with no distinct cleavage planes and the weakest would consist of Quaternary landslide material. In CAMEL, material strength correlates with the susceptibility of a material to move during a seismic event.

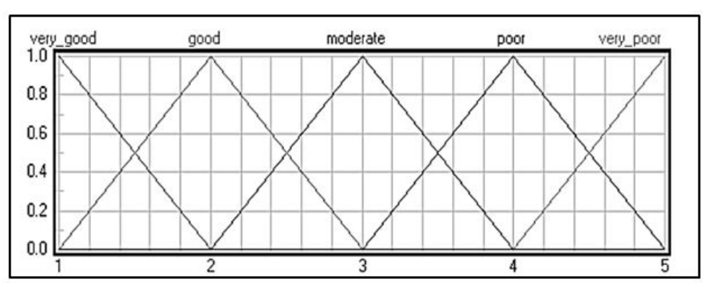

Figure 16: Reference membership function of the material type/geology [8].

The Karonga geology, as discussed in the geology section of the study area, is dominated by the sedimentary Karroo System which overlays the basement complex (igneous and metamorphic rocks). The Karroo system extends from the Permian period to the Triassic period. Since the epicentre of the 2009 Karonga earthquake is located in the sedimentary Karroo system adjacent to the alluvium, the membership function value of material type is derived from the scale value of 3-4 which gives an average value of 3.5. A scale value of 3.5 gives a membership function of 0.7 [(3.5/5)*100]. This implies that the material was very weak and more susceptible to perturbation.

Soil Depth

The data on depth for Karonga, was unavailable and the recommended 3 meters threshold was applied. The threshold is applied since it is the depth at which the CAMEL excludes deep seated landslide from the possibility module[8]. Thus, during this study 3 meters was adopted for soil depth which has an equivalent fuzzy value of 0.5.

Moisture

As it has been demonstrated in the design of the CAMEL approach, the hMoisturevariable, describes the degree to which the analysis ground layer is saturated. The 2009 Karonga earthquake took place in December which is a dry-wet period in Malawi. Based on this the values between 25%-50% (average 37.5%) was applied to derive the membership function. With reference to the standard moisture values (Figure 16) developed by [8].The average value of 37.5% has a membership function of approximately 0.56.

Shake Intensity

ShakeMap offers a representation of ground shaking generated by an earthquake. However, the information ShakeMap was not available for use. Consequently, an estimate of the intensity and PGA were derived by making reference to the MMI table and Representative ShakeMap table. The ground shaking levels at sites throughout the region varies depending on the distance from the earthquake, propagation of seismic waves and the litho logic and soil conditions at sites. In the case of the 2009 Karonga earthquake Mw 6.0 the equivalent intensity of the earthquake falls in the range of VI-VII of the MMI. As demonstrated by[9]. Qu S, et la. And Keefer [10,11]the threshold MMI for occurrence of landslides is VII. This implies that the possibility of landslides occurrence is very low or negligible. Regarding PGA value, MMI of VI-VII, has an estimated PGA values between 0.18 and 0.34 which gives an estimated average PGA value of 0.26 g (Table 3).

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-14	1.4-39	3.9-92	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Table 3: Representative Shake Map as developed.

Discussion

In order establish the possibility of occurrence of landslides during the 2009 Karonga earthquake the information from a number of literature on earthquake induced ladnslides were integral in the determination of the weights of parameters. Weights of parameters were established by using the fuzzy logic component in CAMEL which is integrated in GIS. Table 4 provides a summary of the weights that were determined through critical observation and inferences. The ranking and weighting were performed for topographic parameters (Slope height, slope angle, terrain roughness, and slope aspect), material type, soil depth, and moisture and shake intensity. The weights were then summed up to derive a weighted sum which enabled the inductive drawing of a conclusion. The weighted sum of 0.44 obtained from the analysis is below par for a possibility of occurrence of landslides. This implies that EI landslides would not have occur under these conditions.

Variable	Fuzzy DoS values	Averagefuzzy DoS	Comment (on possibility of occurrence of EI landslides)
Slope Height	0.30-0.50	0.40	Low DoS
Slope Angle	0.20-0.60	0.40	Low DoS
Terrain Roughness	0.35-0.70	0.35	Low DoS
Slope Aspect	0.10-0.60	0.35	Low DoS
Material Type	3.5/5	0.70	High DoS
Soil Depth	0.5	0.50	Average DoS
Moisture	37.5%	0.56	Relatively high DoS
Shake Intensity	0.18-0.34	0.26	Low DoS
Total weighted sum		**0.44**	**Unlikelihood of landslides occurrence**

Table 4: Summary of the fuzzy membership to assess DoS in relation to susceptibility to EI landslides.

Another aspect worthy noting is that the karonga fault has been identified and established as a normal fault[2,3]. The comprehensive review done on over 30 earthquakes that triggered landslides has shown that normal fault type has a very low probability of EI landslides occurrence as compared to thrust fault. One of the reasons is attributable to non-violent nature of the tensile forces operating at normal faulting system. Basically, extensional forces acting on normal faults pull the fault blocks apart in which case the hanging wall moves down along the fault plane relative to the footwall unlike at the thrust fault where the hanging wall rides over the footwall with a violent collision due to compressive forces along convergent boundaries. Thus, by inductive inference the 2009 Mw 6.0 earthquake in Karonga area could not have caused landslides in as far as fault type is concerned. However, surface ruptures were extensively recorded and reported by [3,4].

Conclusion

In conclusion, earthquakes are surely among the main trigger of catastrophic landslide which result in severe human casualties, property losses and environmental degradation. EI Landslides are caused by the interplay of controlling factors: the earthquake parameters (magnitude, PGA, earthquake duration, fault rapture dynamics), and site properties (geology, tectonic settings and topography). Thus, no single factor could be picked out as the dominant causative agent of the EI landslides over the other because the effectiveness of one factor in inducing landslides is dependent on the other factors. Most authors on EI landslides hint that long-term landslides susceptibility assessment has typically put emphasis on rainfall-induced landslides events to model susceptibility as they occur more frequent than EI landslides leading to under-representation of earthquake triggered landslides risk. Under-representation of earthquake-triggered landslides also comes from the evident complexity of analysing EI landslides since it incorporates various disciplines such as geology, geophysics, seismology and geotechnics. It has also been established that CAMEL and GIS can be applied to assess a possibility of landslides occurrence in the absence of landslides data. However, the effectiveness of the predicting the possibility occurrence of landslides relies on the availability of DEM, material type, Shake Map and moisture content which are input variables. A great care must also be exercised during the observation and interpretation of the DoS to draw a conclusion.

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