GIS-Remote Sensing Based Approach in Assessing and Modeling Landslide Vulnerability Areas in Southeast Zone of Nigeria

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Abstract

The study of landslides is essential in order to avoid hazards occurrence, or at least minimize the adverse effects it has on the environment, properties and human populations whenever it occurs. Identifying vulnerable areas, help in putting up measures to protect or avoid such areas which in a long way reduces the risk associated with the adverse effects of landslide. The study used primary and secondary data that consist of field observation, photographs and other literature from which the likely triggering factors of slope, land use land cover change (LULCC), aspect, soil texture and type, curvature, drainage density, elevation, lineament density, normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), geology, topographic wetness index (TWI), geomorphology, rainfall, temperature, wind speed, wind pressure, population, river channels and road network construction were extracted. The satellite imageries (SRTM and Landsat 8 OLI-TIRS) data were obtained from USGS Earth Explorer, processed and modeled based on the triggering factors using ArcGIS v10.4, while visits were made to the various parts of the study area for validation and confirmation of results. Microsoft Excel 2007 was used to compute and assign weights to the triggering factors; experts' knowledge was sought in regrouping the factors, while weighted overlay methods in the spatial analyst tool of ArcGIS v10.4 were applied to generate the model of landslide vulnerable areas in the study area. The study recommended among other things creating a regional body vested with powers and resources to effectively monitor the environment, providing alternative means of livelihood that will discourage mining, deforestation, forest fire, and overgrazing, and encourage sustainable resource use and management that will not expose the areas to the triggering factors of landslide.

Keywords: Geographical Information System, Remote Sensing, Model-map, Landslide Vulnerability Areas, Southeast Zone

1. Introduction

Landslides occurrence can bring about a long-lasting effects or changes on the environment in the form of topography or terrain adjustment, alteration in river courses and patterns of flow, triggering of tsunami in the case of coastal and undersea slides, alteration of forest landscapes and wildlife ecosystems, geographical locations of farm lands as well as covering of agricultural soils and roads from nearby slopes, and disruption of traffic (Geertsema et al, 2009). Landslide has cause an estimated 1016 deaths globally, and an economic losses in the tune of 4 billion US dollars on an annual basis (CRED, 2016). This catastrophic loss is because of increased and uncontrolled deforestation, unregulated soil mining, unsustainable slope cutting during road constructions, haphazard development leading to unplanned urban growth and the effects of climate change induced weather elements (Kanungo et al, 2008; Igwe, 2013; Igwe, 2015). Lives are lost and properties destroyed due to landslides at a global scale which accounted for about 9% of total global natural disasters (Smith and Petley, 2009). Landslides have generally impacted negatively on the environment and its socioeconomic costs implications on human populations are underestimated due to some unrecorded landslide occurrences (Okagbue, 1989).

Study of landslide is very necessary in order to avoid hazards occurrence, or at least minimize the adverse effects related to it on the environment, properties and human populations generally whenever it occurs. Identifying vulnerable areas, help in putting up measures to protect or avoid such areas which in a long way reduces the risk associated with the adverse effects of landslide. Landslide vulnerable areas can be identified using various methods which include; (i) The physically based approach and (ii) phenomenological model for predicting mass movements adopted by Calvello et al, (2008) and Federico et al, (2012). Predicting landslide can be done physically based on the understanding and composition of rocks type, soils and the geologic properties (Corominas et al., 2005; VanAshch et al., 2007; Sassa et al., 2010), while empirical approach with reliance on data acquisition and analysis can be employed to monitor continuously all relevant factors likely to induce mass movement or falls that may eventually trigger landslide. Parameters of soil constituents whose physical and or chemical alterations and movements specially along geologic boundary lines can be monitored with the use of remote sensed satellite image data and geographic information system (GIS).

The relationship between natural and anthropogenic activities led landslide, and human settlements necessitate the need for monitoring, which is made possible with the availability and use of geographic information system (GIS) and remote sensing (RS) technologies. The access to these technologies has improved the production of landslide vulnerability maps through the allowance of systematic acquisition of data of large and inaccessible areas at reduce or no cost, and optimization of field verifications (Guzzetti et al, 2012).

There are occurrences of landslide in South East Nigeria, of which no single cause is being attributed to it. There is a number factors and conditions that must be met and or usually interact to make the soil vulnerable to sliding (Igwe, 2015). Some researchers had identified some of the factors that can initiate or trigger landslides within the area as rainfall, gully erosion, anthropogenic activities, geology, elevation, slope angle and soil texture and type (Okagbue 1989; 1992; Igwe, 2015). Others are land use land cover change (LULCC), aspect, curvature, drainage density, lineament density, normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), topographic wetness index (TWI), geomorphology, temperature, wind speed, wind pressure, streams head cut, settlements, and roads network construction (Cao et al, 2021; Effiong et al, 2021; Woldearegay, 2013; Wubalem and Meten, 2020; Shahabi and Hashim, 2015; Ayadiuno et al, 2022). These factors whose combined present or absent are capable of triggering landslide have caused avoidable severe destructions and unquantifiable losses in the study area. Hence the need to identify and map these areas that are vulnerable to landslide upon the combined present or absent of some of the factors capable of triggering landslide as well as rank the landslide vulnerability and causative factors according to their weight of influence.

2. Study Area

The study area is Southeast Nigeria which comprises of five core indigenous Igbo speaking States of Nigeria. The States are Abia, Anambra, Ebonyi, Enugu and Imo. The States formed the Southeast geo-political zone, one of the six geo-political zones in Nigeria and lies between 4° 21′ - 7° 14′ north and 6° 37′ - 8° 29′ east (Ndulue at el, 2021), with a land mass of about 29,525km^2 and projected population of about 25,911,711 persons, making it the zone with the highest population density in Nigeria, hence the pressure on limited land resources in the zone. The zone shares boundary with Benue and Kogi States to the north (North Central geo-political zone), Rivers State to the south, Akwa Ibom to the southeast, Cross River States to the east and Delta State to the west (South South geo-political zone) (Akukwe et al, 2018) (Figure 1).

The area is known for the prevalence of ravaging gully erosion which has eluded so many containment measures, resulting to lives, lands, and properties being lost (Grove 1951; Ofomata, 1964, 1965, 1975, 1978, 1981, 2001; Egboka, 2004; Hudec et.al 2006; Mozie, 2010; Ezezim, 2010; Dim, 2014). South East Nigeria is made up of five predominantly geologic formations which are Ogwashi/Asaba or Benin formations (Alluvium), Nanka Sands, Bende/Ameke formations, Nsukka formations (Laterite), Enugu/Nkporo - Awgu formations (Shale), and Benue – Abakiliki formations (Dolomitic Limestone). The geology is more of sedimentary composition, mainly of marine-derived friable sandstones and sands on the surface, while beneath the surface is of shale deposits. Benin formations was developed as a result of the formation of the Benue trough as a failed arm of a rifting associated with the drifting of African and South American continent that opened up the Atlantic (Evamy et al., 1978). The crust of the area had been subjected to tectonic pressures that resulted in several cycles of folding and faulting. Subsequent exposure to climatic elements has also resulted in deeply weathered materials that formed the lateritic crusts of varying degree of thickness (Ofomata 2001; Umeji, 2001; Aneke, 2007).

Following Koppen’s climatic classification, the study area is characterized by a tropical savannah climate in the south and middle and warm semi-arid climate in the north. The study area is covered with these agro-ecological zones; tropical rain forest in the south, mid-latitude zone in the centre, and derived savannah in the north (Anyadike, 2002). The area has seven to nine months of rainfall which varies in amount, intensities and duration from 68 to 116 mm/hr-^{1} with an average of 2.86 hours (Eze, 2014). The mean annual rainfall is between 900 and 2400 mm and an average annual temperature range of between 19 and 37^{0}C (Anyadike, 2002). The mean erosivity of the rainfall determined according to the formula of Kim, Kim et al, (2003) was 83.75 mm, which is highly erosive. The altitude of the study area ranges from 11 to 550 m above sea level with a mean elevation of 400 m. The population density of the study area averaged about 950 pers/km^2, with urban centers having a range of about 1200 to 8400 pers/km^2 (NPC, 2006; https://citypopulation.de/php/nigeria-admin.php?adm2id=NGA004006). The relatively high population resulted in the near total clearance of the pristine vegetation of tropical rain forests (Igbozurike, 1978). The parts of the area that are relatively high, with sandstone and sand geologic formations are practically urban or sub-urban areas, this is due to the areas' suitability for engineering constructions that supports settlements (Ofomata, 2001; Umeji, 2001; Ayadiuno et al, 2021). The soil in the study area is rated as generally exhausted due to intensive uses resulting from progressively shortening fallow periods (Igbozurike, 1978) (Figure 1).

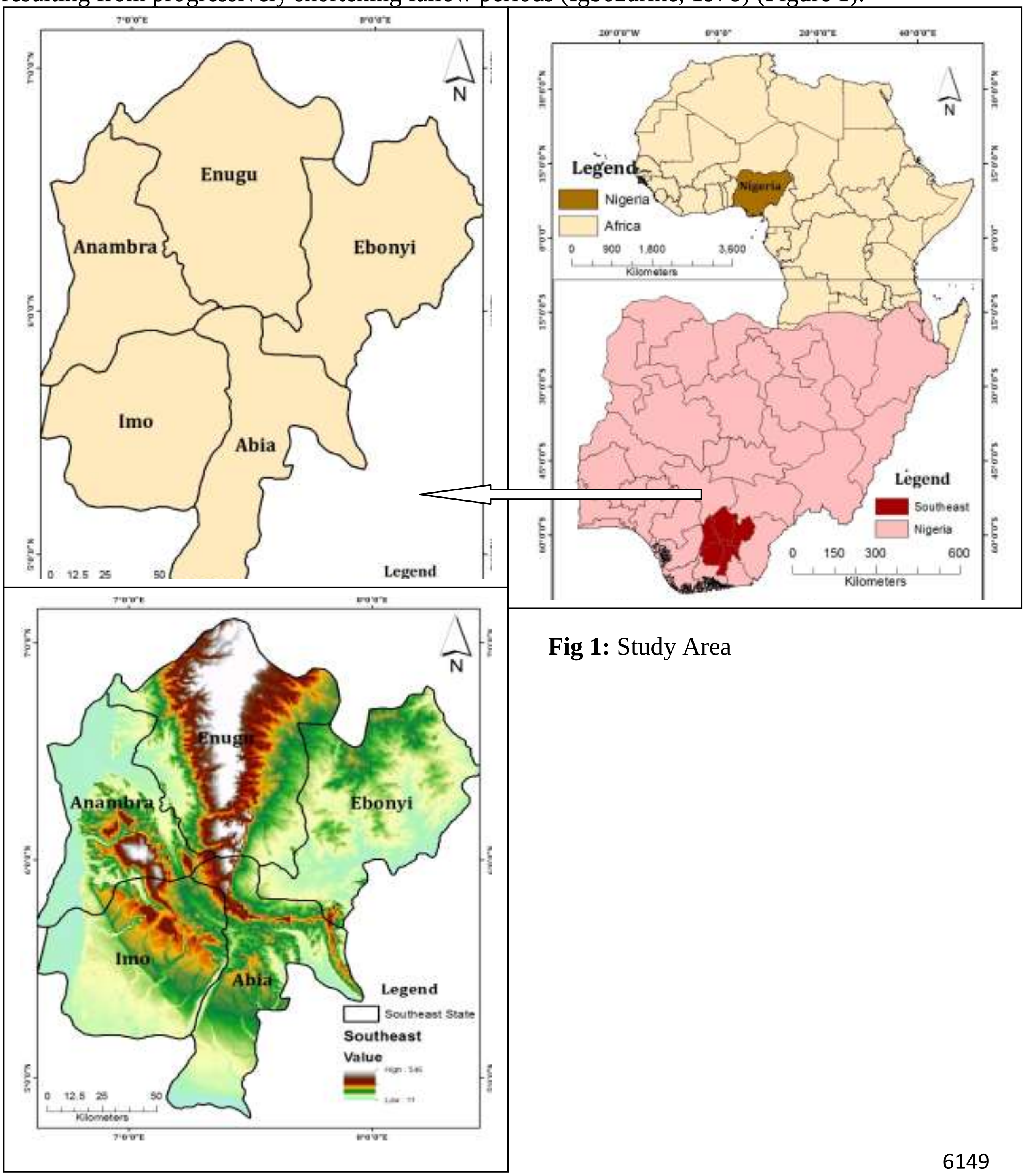


Fig 1: Study Area

3. Materials and Methods

3.1 Data collection

The data required for this study were of primary and secondary in nature. The primary data included field visit for physical observation, measurements and photographs. The secondary data consisted of satellite imageries (SRTM and Landsat 8 OLI-TIRS) data extracted from USGS Earth Explorer (www.earthexplorer.org); climatic data (https://power.larc.nasa.gov/data-access-viewer/); soil data (www.fao.org); and anthropogenic data (www.diva-gis.org), as well as other literature from which the likely landslide triggering factors – slope angle, land use land cover change (LULCC), aspect, soil texture and type, curvature, drainage density, elevation, lineament density, normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), geology, topographic wetness index (TWI), geomorphology, streams channel, rainfall, temperature, wind speed, wind pressure, settlements, and road networks construction were extracted (Table 1).

Table 1: Data used for the analysis of triggering factors of landslide in the study area

Data	Sources	Map
Satellite imageries (SRTM and Landsat 8 OLI-TIRS)	USGS Earth Explorer	Slope angle, land use land cover change (LULCC), aspect, curvature, drainage density, elevation, lineament density, normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), geology, topographic wetness index (TWI), geomorphology, and streams channel
Climatic data	https://power.larc.nasa.gov/data-access-viewer/	rainfall, temperature, wind speed, wind pressure
Soil data	www.fao.org	soil texture and type
Anthropogenic data	https://www.diva-gis.org/	settlements, and road networks construction

3.2 Data, process and mapping methods

The satellite imageries were processed and landslide related factors were mapped (Figure 3) as likely triggering factors and rendered in a format suitable for further analysis required to generate a model map of landslide vulnerability zones in the study area using ArcGIS v10.4. Microsoft excel 2007 was used to compute and assigned weights to the triggering factors while weighted overlay methods in spatial analyst tool of Arctool box in ArcGIS v10.4 were applied in mapping the landslide vulnerable areas in the study area (Figure 2). Validation visits were made to confirm result.

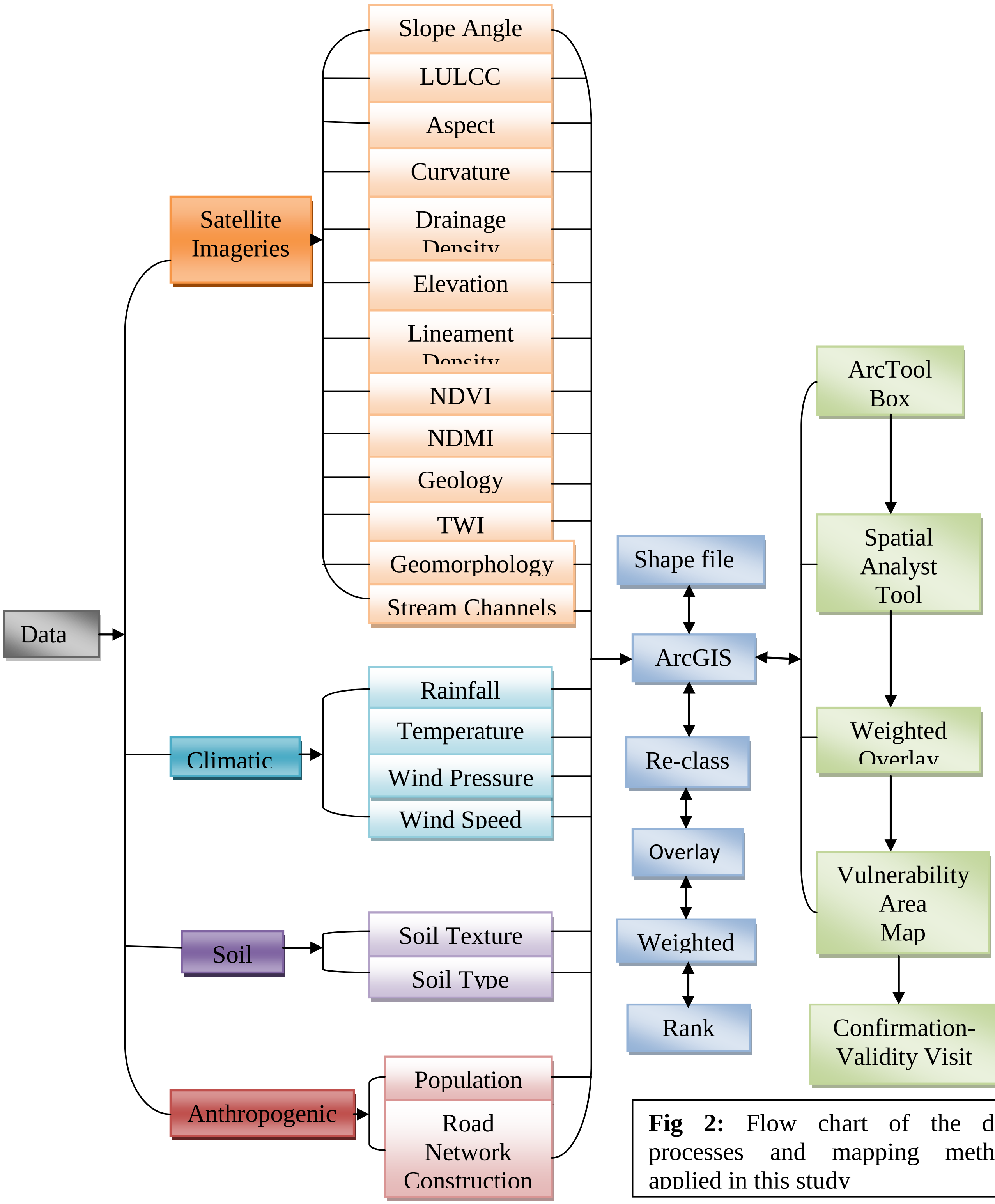
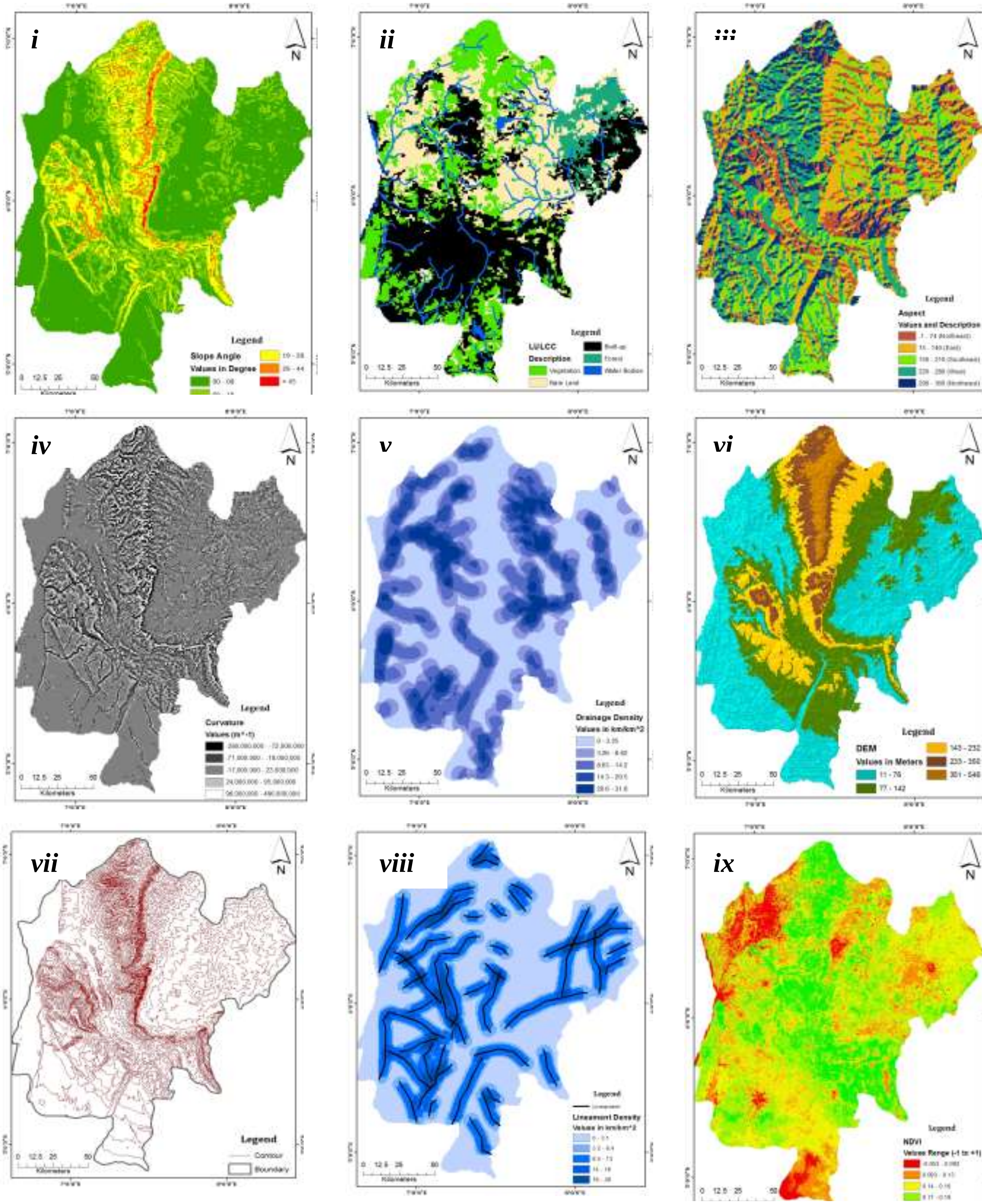
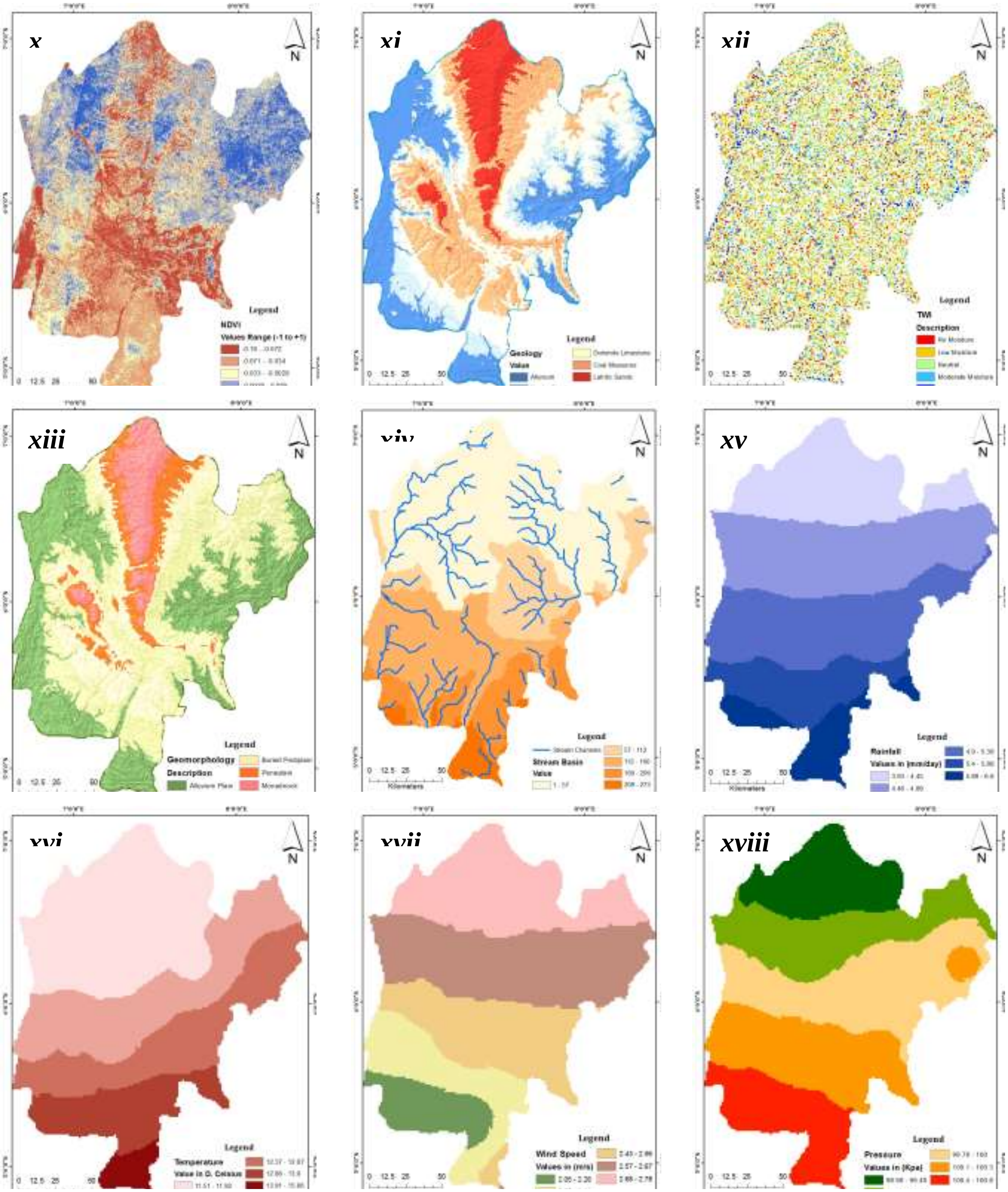


Fig 2: Flow chart of the data, processes and mapping methods applied in this study


i
ii
iii
iv
v
vi
vii
viii
ix
N
Legend
Slope Angle
Values in Degree
LULCC
Description
Built-up
Forest
Vegetation
Water Bodies
Aspect
Values and Description
Curvature
Drainage Density
DEM
Values in Meters
Contour
Boundary
Lineament Density
NDVI
Kilometers


x
NDVI
Values Range (-1 to +1)
Legend
xi
Geology
Value
Legend
xii
Legend
TWI
Description
xiii
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Geomorphology
Description
Stream Basin
Value
Legend
xv
Legend
Rainfall
Values in (mm/day)
Kilometers
Legend
Temperature
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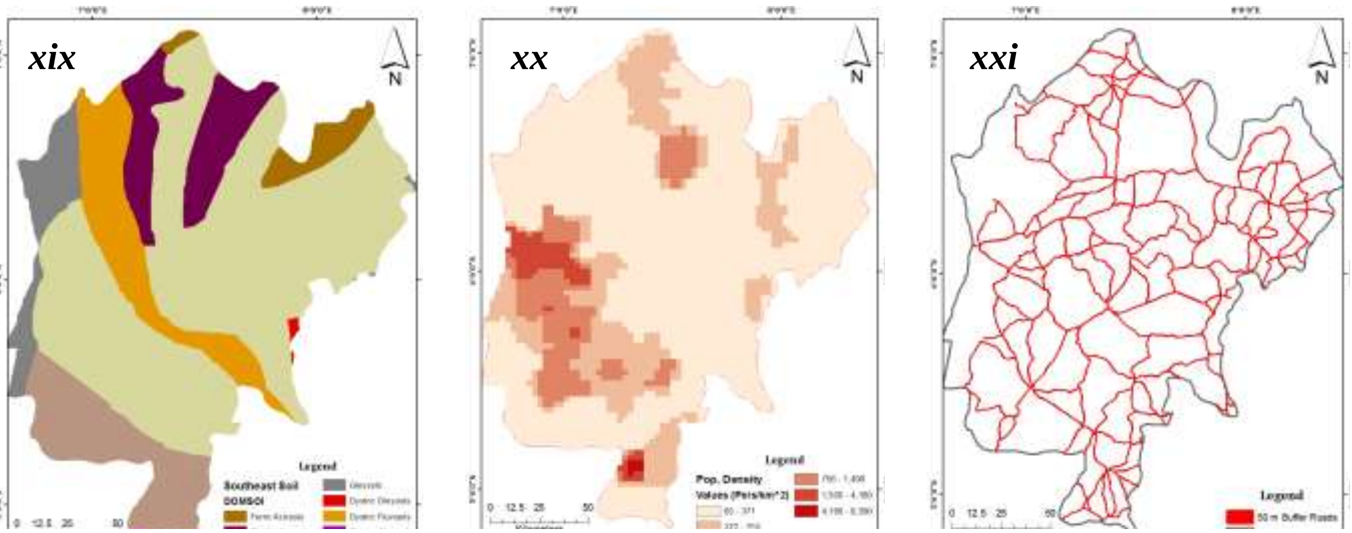
Legend
Wind Speed
Values in (m/s)
xviii
Legend
Pressure
Values in (Kpa)



Figs. 3*i* – 3*xxi*: Triggering factors of landslide

Photographs by Ndulue: Slope created as a result anthropogenic activities in the study area (a: Landscape modification for engineering construction and b: hill cut for road construction)

4. Results

4.1 Map representation of the triggering factors of landslide in the study area

Map analyses of the triggering factors of landslide in the study area were carried out, and the results were also presented as follows:

4.1.1 Slope

The slope angle is a very important criterion in determining landslide vulnerability areas. Slope angles that are very steep are very likely to slide depending on the composition of the materials and the inclination. It discourages infiltration and encourages surface runoff. High runoffs on sandy geologic materials are likely to trigger landslide. A slope angle map can be extracted from the SRTM/DEM data using ArcGIS software (Szabó et al. 2015; Rawat et al. 2018). The slope angle map of the study area was categorized into five classes - flat (0 - 8^0), near slope (9 - 18^0), moderate slope (19 - 28^0), steep slope (29 - 44^0), very steep slope (45 - 90^0) (Figure 3*i*)

4.1.2 Land use land cover change (LULCC)

The use of land for different purposes affects the geology, terrain and landscape of that area. LULCC of the area in this study was extracted from the USGS satellite imageries using visual interpolation techniques in ERDAS IMAGINE v9.2 software. The category of LULCC required in this study is five classes – settlement/built-up, vegetation, bare land, water bodies, and road network, which has been analyzed and mapped. The majority of the study area is covered with settlement/built-up (39.90%), vegetation (26.36%), bare land (27.05%), forest (5.75%), and water bodies (0.94%). Each category in the land use land cover class in one way or another to encourage or discourage anthropogenic activities that may trigger landslide (Figure 3*ii*).

4.1.3 Aspect

Aspect depicts the direction that slopes of the terrain face. Output raster dataset indicates the value of the compass direction of the aspect. 0° represents the true north direction; 90° represents the east direction, and so on. It influences significantly the local climate of an area, its vegetation type and density, precipitation, insolation, temperature, melting of snow, agriculture, ecosystem and settlement pattern (Swatantra et al. 2015). The terrain side that faces the sun experiences more evapotranspiration, increased energy availability and intake for the vegetations, increased water absorption for replacement in the area and therefore reduces runoff and infiltration which maintains balance during the rainy season (Wilson and Gallant, 2000a). The side opposite the direction of the sun may not be so vegetated, thereby generating more runoffs and or infiltration that may trigger landslide (Figure 3*iii*)

4.1.4 Curvatures

Curvatures are of two types - Plan and Profile curvatures. Plan curvature is the contour line formed by the intersection of the horizontal plane with the surface (Wilson and Gallant, 2000a). It is also seen and considered as the geometry of the earth’s surface and describes the changes of slopes inclination and aspect (Nefeslioglu et al, 2008). The curvature displays the shape or curvature of the slope of the drainage basin where it helps to demonstrate the erosion and runoff processes. The profile curvature depicts the rate at which the morphology of the terrain’s potential gradient changes the velocity of flow and the process of sediment transport (Rajith et al, 2019). Curvatures depict the distribution of convex and concave nature of the terrain in a given location (Mitasova and Hofieka, 1993) (Figure 3*iv*).

4.1.5 Drainage density

The streams length divide by the unit area of the catchment is known as the drainage density (Horton 1945; Strahler 1952). Drainage density that has high value indicate areas of low surface runoff and high infiltration rates, while drainage density that has low value indicate areas of high surface runoff and low infiltration rates. The drainage density (Dd), is determined using

$Dd = L_S/A$ ………..(Eqn 1)

where Dd represents drainage density and L_S represents the total streams' length. The Drainage density class was divided into five to correspond with other factors. Their ranges are very low, low, moderate, high, and very high (Figure 3*v*)

4.1.6 Elevation

Digital elevation model is used to depict the variations in the terrains' height. The data for model was extracted from SRTM/DEM and modeled in ArcGIS. The model allows for the visual account of the range in the altitude in the study area. In order to conform to the classes of other factors, the variations in height were classified into five - the highest height is about 550 m, in the central to northern part of the Enugu States, followed by another class of 385 m, in Anambra, and Abia States respectively, while Imo and Ebonyi States have highest heights of 350 m and 145 m respectively. All the States have an undulating to near flat terrain of about 11 m (Figure 3*vi*)

4.1.7 Geology

Geology is considered as one of the controlling factors influencing landslide occurrence. The serial arrangement of different rock beddings and structural disconformities of lithological units and their interaction surface or subsurface flow can initiate sliding. Porosity and permeability of the litho units above and the impermeable beddings below can encourage storage and transmissivity of groundwater which can also encourage landslide due to the existence of different rock beddings and structural disconformities in the area (Figure 3*xi*)

4.1.8 Lineament density

Hydrogeological condition is as a result of openings in the crust of that area. These openings can be in form of voids, pore spaces, joints; fault lines, fractures, and bedding planes. Primary and secondary porosity is an important determinant of Lineaments which are linear features of tectonic origin or later applied pressure on or beneath the earth surface. Due to their linear, direct, curvilinear form, they can easily be demarcated in satellite imagery. Some other indications like tone, texture, relief, drainage, and vegetation soil tone's linearity also give valuable information for lineament differentiation. Structural features effect like lineaments created by tectonic or applied pressure on or beneath the earth surface can be a boundary of uplift of subsidence of earth crust (Solomon, and Ghebreab, 2006), and subsequently an area likely to trigger landslide (Figure 3*viii*).

4.1.9 The Normalized Difference Vegetation Index (NDVI)

This is a statistical indicator that ascertains the physical condition of vegetation using the visible and near infra-red bands of electromagnetic spectrum. The yielding values are between -1.0 to +1.0, higher NDVI values indicates that there is a greater abundance of vegetation captured as a result of the presence of their chlorophyll, which indicates healthy productive vegetation (Weier and Herring, 2000; www.usgs.gov). NDVI for this study (Figure 3*ix*), is calculated from Landsat 8TM data of 2021. The NDVI calculation is as follow:

$NDVI = \frac{Near\ IR\ Band - Red\ Band}{Near\ IR\ Band + Red\ Band}$ …… (Eqn 2)

4.1.10 Normalized difference moisture index (NDMI)

Normalized Difference Moisture Index (NDMI) is used to determine vegetation water content (www.usgs.gov). Some researchers have tested for the NDMI using band ratio in Landsat 8 imagery to identify the moisture content of soil and rock surface and interpret same in order to determine the soil moisture levels and the relationship with soil types (Jimmy et al, 2020). It is calculated as a ratio between the NIR and SWIR values in traditional fashion.

NDMI = $\frac{(\mathrm{NIR} - \mathrm{SWIR})}{(\mathrm{NIR} + \mathrm{SWIR})}$ ……….(Eqn 3)

The vulnerability of an area to landslide is directly depends on the availability of moisture in the area. They can be in form of natural groundwater - temporary or permanent spring sources, surface water flow or moisture from precipitation (Kravchynskyi et al, 2021) (Figure 3*x*).

4.1.11 Topographic wetness index (TWI)

Topographic wetness index (TWI) was propounded by Beven and Kirkby (1979), and it measures the potentials of flow intensity and rate of accumulation of moisture. TWI can also mean Topographic Moisture Index (TMI); it measures the influence of topography, the extent or rate at which saturation occur and subsequent generation of runoff at the source areas on the environment (Wilson and Gallant 2000b). The TWI of the study area was extracted from the DEM generated from the SRTM data using a raster calculator in ArcGIS v10.4. Higher values show areas with wetter condition (high moisture), while the lower values show areas with drier condition (less moisture). TWI of the study area (Figure 3*xii*), is calculated using:

TWI = int $\left(\frac{Catchment\ Area}{\tan\beta}\right)$……..(Eqn 4)

where tan β = *slope in angle.*

4.1.12 Geomorphology

Geomorphology is the process that forms the surface landforms. Landforms characteristics determine areas that are likely to be vulnerable to landslide. Satellite imagery can be analyzed and used to map land surface of an area showing the variations in size, shape, tone, texture, relief, location, association, physiographic, landforms, rock types and formations as well as the geological structures (NRSC 2010). Geomorphological features within an area is based on the erodibility and resistance of rock materials in the area, which determines the variations in height of the out crops (erodible areas) and other surfaces - the buried pediplains, pediment zones, alluvial plain, and valley floors (depositional areas). The process of uniformity of land surfaces can be in form of landslide (Figure 3*xiii*).

4.1.13 Stream channels

Meandering is one of the most common attribute of streams channel (Imran et al, 1999). Streams meandering are of two types – meandering by different circulation regimes and around the slope base (toe). Meandering by different circulation regimes occur when the secondary circulation brings water slowly toward the inner bank, and the primary circulation with fast moving surface water flows toward the opposite direction (outer bank). The channel curvature has a way of sustaining self especially at the bends. As the river erodes the outer bank at a bend, depositions are made on the inner bank and therefore maintaining an equilibrium which keeps the width size constant (Imran et al, 1999). The second type of meandering occurs when rivers flow around the slope base (toe) (Othus 2008). Examples of river induced landslide are found globally - landslide initiated debris that covered the ravine of Brusnik Stream in Slovenia and shifted its course (Mikos et al, 2006), landslides in the northern part of the Owyhee River, Oregon (USA) where the river channel curved around the toe of a slope, offsetting the course of the river channel (Othus 2008) (Figure 3*xiv*).

4.1.14 Rainfall

Rainfall is tentatively regarded as primarily the source of runoffs that may trigger landslide. Areas of high rainfall distribution with steep surface slopes may influence high runoff and low infiltration rate, which subsequently may render such areas vulnerable to landslide. The study area experiences heavy rainfall from April up to September with maximum amount of rainfall recorded at approximately 2400 mm ((Inyang, 1975; Anyadike, 2002; Ayadiuno et al, 2021). The data were mapped and grouped into five classes – very low, low, moderate, high, and very high, for ease of identifying areas and their various degrees of rainfall distributions (Figure 3*xv*).

4.1.15 Temperature

Temperature is the degree of hotness or coldness of an area. High temperature increases evaporation, leaving the area very dry or in drier condition. Such condition in an upland region with friable soils formation that is loose may encourage mass movement. Temperature is also a key factor in rock weathering, where the process of contraction and expansion as a result of dryness and wetness of an area can initiate cracks that are likely to trigger landslide (Figure 3*xvi*).

4.1.16 Wind speed and pressure

Heavy rainstorms are major contributor to landslide occurrence in mountainous regions. Heavy storms are always associated with heavy wind with immense speed and pressure. The interaction of a heavy wind with heavy storm in an area whose topography is vulnerable to sliding can trigger landslide in upland catchments (Rulli et al, 2007). Wind as a climatic variable can trigger landslide in an area that is vulnerable. Having this understanding of the effects of such physical processes triggering landslide is necessary in evaluating slope stability and predicting landslide occurrences (Figure 3*xvii*).

4.1.17 Soil texture and type

The soil texture of an area plays a role in determining the surface runoff/infiltration ratio of rainwater flow. Soils that are mostly sandy have low runoff and high infiltration rate because of their porosity and friable nature, while soils that are mostly clayey have high runoff and very low infiltration rate. Soil particle sizes can be used as a parameter for identifying landslide vulnerable areas. The soil type in the study area based on texture consists of sandy loam, sandy clay, loam, clay loam, and clay soil; and on particle sized, silt, fine sand, coarse sand, and clay (Ndulue et al, 2021; Ayadiuno et al, 2021). Sandy soil has a high infiltration rate due to their porosity and friable nature. Soils of this nature are susceptible to disintegrate and cause landslide in an area with high elevation and steep slope, while clayey soils are elastic in nature and offer resistance to infiltration instead creates a water log or runoff scenario (Figure 3*xix*). The study area consists of average silt (0.56%), fine sand (28.22%), coarse sand (43.40%), and clay (17.82%) respectively (Ayadiuno et al, 2021).

4.1.18 Settlement/Population

Settlement can also mean the population of an area over time with their socioeconomic (anthropogenic) activities. Settlements are dynamic, they expand as the population grows, as population grows, the need for land use also grows which lead to exploitation of economic materials like stones and sands for building, spaces for engineering constructions (Mozie and Ayadiuno, 2008), roads for ease of accessibility among others. Anthropogenic activities like mining at the base of a slope (toe), road cut at a slope, which leaves the residual at an angle likely to cause slope failures, pressure of overloading at the top of an unsuitable slope, and agricultural (cultivation) practices on the slope (Sissakian et al, 2004), removal of vegetative covers for urban development (Egboka, 2019) among others (Figures 3*xx*, and 3a).

4.1.19 Road network construction

The activities of every settlement depends on a well organized transportation system, a smooth, comfortable, fast, shorter, efficient and healthy urban and or rural mode of mobility that the various economic activities required. The need to achieve a road network connections that will serve the area as well as all the socioeconomic activities of the settlement, must link agricultural, mining and other areas of primary economic activities. Roads meant to connect these areas of primary economic activities and or other settlement with spatial interactions must in most cases cut through slopes. When slopes are cut in a way that the slope stability is threatened, sliding becomes inevitable. Other threats of road network construction include space absorption by highways, energy consumption, and ecological consequences, like flooding, landslide, among others (Cao, 2021; Effiong et al, 2021) (Figures 3*xxi*, and 3b).

4.2 Percentages of reclassified landslide causative factors

Map analysis of the causative factors classified into five shows where their impacts are likely to be felt heavily in the study area following the effects of either their lows or highs as the case may be. Table 2 and figure 4 show the percentages of various classes of the mapped causative factors.

Table 2: Factors whose highs or lows contribute to triggering landslide

Reclass	SLP	LU	ASP	CURV	DD	ELEV	LD	NDVI	NDMI	GEOL	TWI	GEOM
1	55.56	26.36	16.49	3.89	39.43	46.19	42.73	16.65	14.46	46.53	9.57	33.03
2	26.97	27.05	21.33	19.08	19.52	29.32	18.05	26.42	27	28.92	38.04	30.46
3	13.05	39.9	20.85	59.93	21.96	13.69	28.34	22.78	33.23	13.76	32.95	18.85
4	4.12	5.75	25.05	14.35	13.64	6.89	6.53	23.16	19.68	6.92	15.1	9.07
5	0.31	0.94	16.28	2.75	5.44	3.91	4.35	10.99	5.62	3.87	4.35	8.61
Total percentage	100	100	100	100	100	100	100	100	100	100	100	100

Total_Per_High/Low	4.43	27.05	32.77	22.97	58.96	10.8	10.88	43.07	41.47	10.79	47.61	17.67
Ave_Per_High/Low	0.79	4.83	5.86	4.1	10.53	1.93	1.94	7.7	7.41	1.93	8.51	3.16

Note the following: SLP (slope), LU (land use land cover change), ASP (aspect), CURV (curvature), DD (drainage density), ELEV (elevation), LD (lineament density), GEOL (geology), GEOM (geomorphology), STRM_C (stream channels), TEMP (temperature), WIND_P (wind pressure), WIND_S (wind speed), SOIL_TT (soil types and texture), and ROAD (road network construction).

Reclass	STRM_C	RAINFALL	TEMP	WIND_P	WIND_S	SOIL_TT	POPULATION	ROAD
1	46.55	22.49	37.38	15.54	8.83	11.38	68.93	22.61
2	14.97	30.42	25.58	19.84	14.76	12.2	18.73	30.87
3	23.72	25.87	20.91	27.17	21.03	15.85	9.3	23.82
4	10.67	12.86	13.05	22.8	30.83	21.14	2.86	16.5
5	4.09	8.36	3.08	14.65	24.55	39.43	0.18	6.19
Total percentage	100	100	100	100	100	100	100	100
Total_Per_High/Low	14.77	21.22	16.13	37.46	55.38	60.57	3.04	22.7
Ave_Per_High/Low	2.64	3.79	2.88	6.69	9.89	10.82	0.54	4.06

Figures in red are the percentage of highs and lows of factors capable of triggering landslide in the study area,

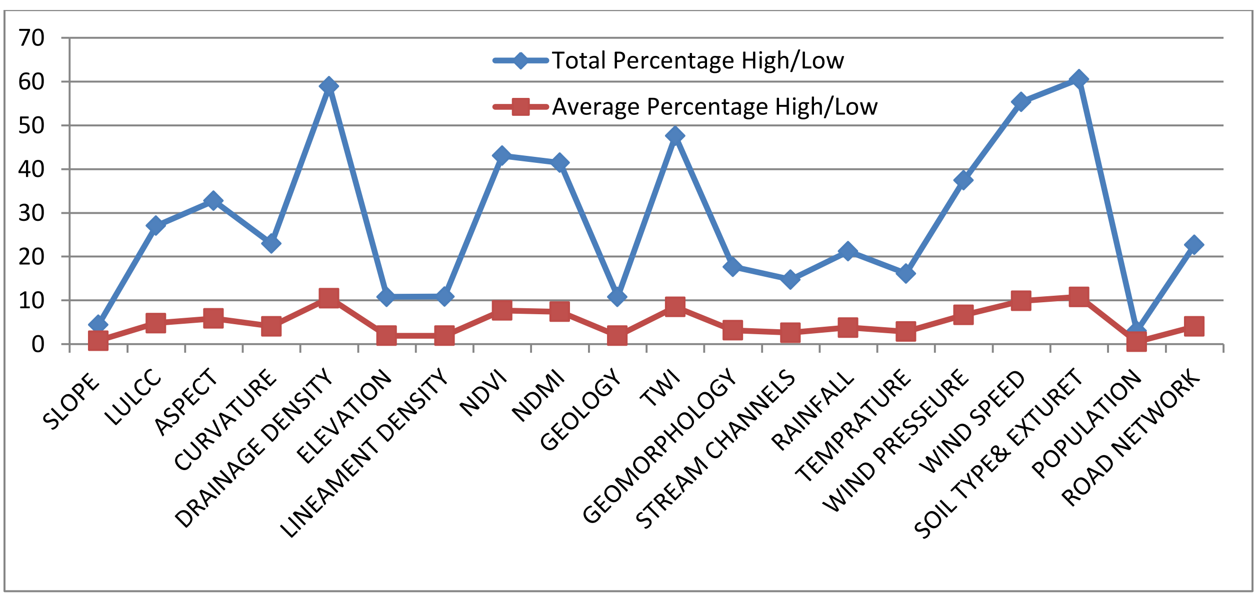


Fig. 4: Factors whose highs or lows contribute to triggering landslide

Some of literature consulted (Wilson and Gallant, 2000a; 2000b; Nefeslioglu at al, 2008; NRSC 2010; Swatantra et al. 2015; Szabo et al. 2015; Rawat et al. 2018; Abija, 2019; Malka, 2021), experts opinions (best judgment, expert knowledge and stakeholder approval) in the field of study, and observed trend of the outcome of overlaying the factors over each other in ArcGIS aided in the categorization of the triggering factors based on their similarity in order to reduce redundancy (Magliulo, 2012), and were grouped as terrain features, anthropogenic and climatic factors. The authors observed from the interactions with experts and the literature, that factors under terrain features either contribute to slope initiation or are derivatives of slope, factors under anthropogenic are the consequences of the actions and the outcome of alterations caused by the human population, while the climatic factors are responsible for rainfall or are the derivatives of it. These efforts were made to avoid using mathematically related factors because they may produce a double effect or inconsistency in the production of the vulnerability map (Conforti et al, 2011; Magliulo, 2012). The structure below (Figure 5) shows the scores of the causative factors used in modeling the landslide vulnerability map. The scores are the average percentages from the percentages of the highs and lows of the causative factors whose effect can initiate or trigger landslide using the formula:

$$\%\%H/L = \frac{\%H?L}{\%TH/L} * 100 \quad \text{………(Eqn 5)}$$

Where %%H/L represents percentage of percentage highs and lows of the causative factors affecting landslide, %TH/L represent percentage areas of total highs and lows of the causative factors affecting landslide.

The percentage scores were inputted in the Spatial Analyst Tools, Overlay and Weighted Overlay in ArcToolbox of ArcGIS to generate the model-map of landslide vulnerability areas (Figures 6 and 8).

Causative Factors	Total Percentage High/Low	Average Percentage High/Low	Score
SLOPE	4.43	0.79	
LULCC	27.05	4.83	
ASPECT	32.77	5.86	
CURVATURE	22.97	4.1	
DRAINAGE DENSITY	58.96	10.53	Slope (52%)
ELEVATION	10.8	1.93	
LINEAMENT DENSITY	10.88	1.94	
NDVI	43.07	7.7	
NDMI	41.47	7.41	
GEOLOGY	10.79	1.93	Population (25%)
TWI	47.61	8.51	
GEOMORPHOLOGY	17.67	3.16	
STREAM CHANNELS	14.77	2.64	
RAINFALL	21.22	3.79	
TEMPRATURE	16.13	2.88	Rainfall (23%)
WIND PRESSEURE	37.46	6.69	
WIND SPEED	55.38	9.89	

SOIL TYPE& EXTURET	60.57	10.82	
POPULATION	3.04	0.54	
ROAD NETWORK	22.7	4.06	

Fig 5: Structure of groupings and assigned scores

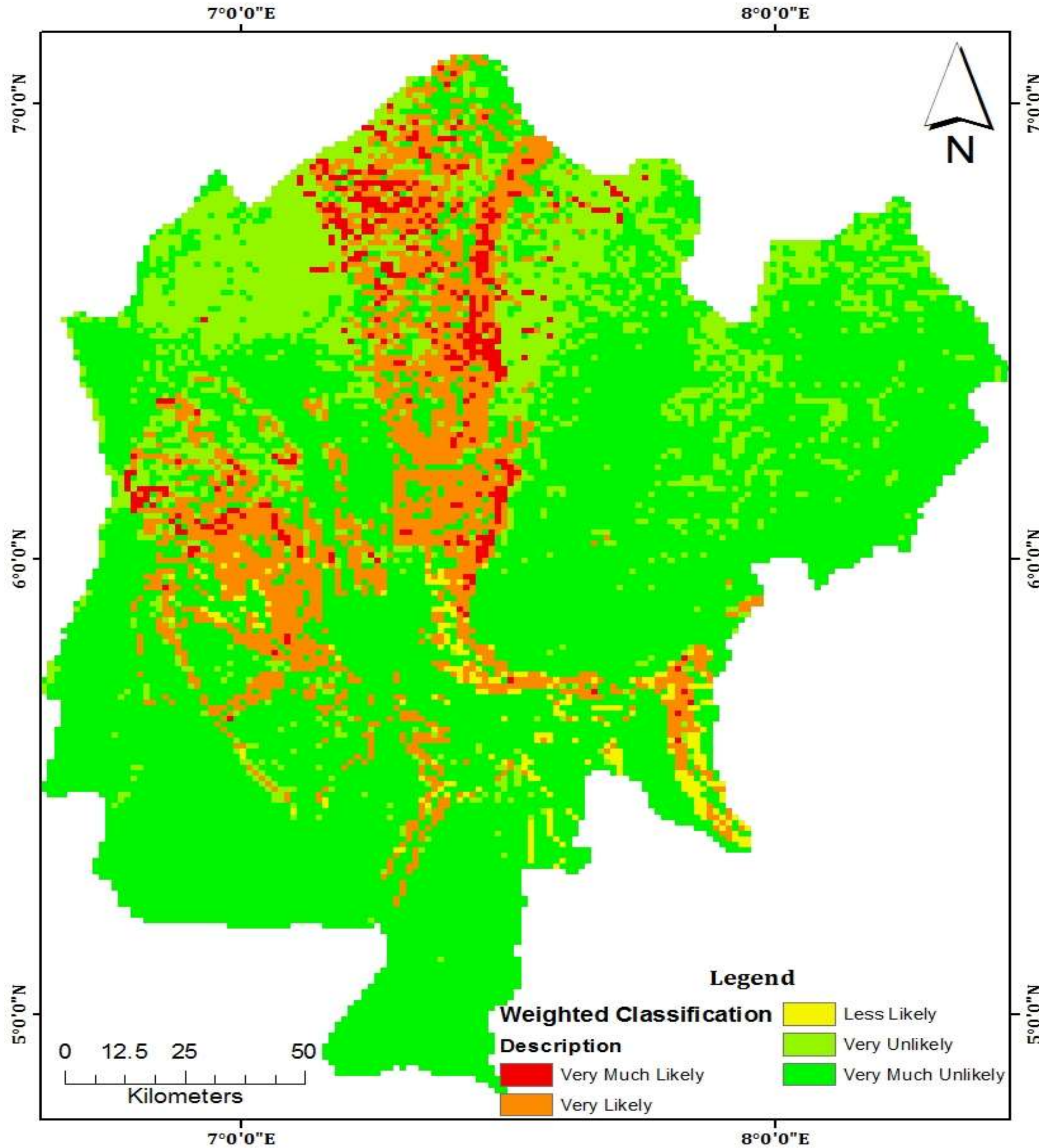


Fig. 6: Landslide vulnerability area in Southeast, Nigeria

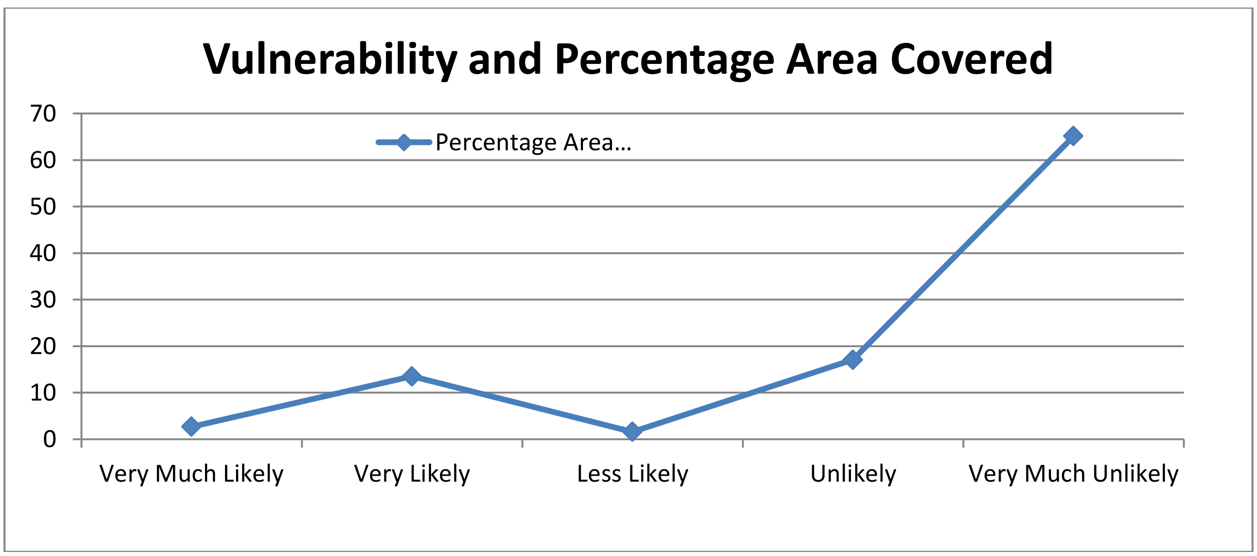
5. Discussion

The landslide vulnerability analysis and modeling involves the use of GIS in producing thematic layers of all the causative factors (Figure 3). The thematic maps were classified and their percentages calculated using Excel spreadsheet. Based on the supposed level and or rate of contribution to causing landslide, scores were assigned to them as well as grouping based on their similarity, and were subjected to further analysis to generate the landslide vulnerability map. The landslide vulnerability map of the study area is presented in figures 6 and 8.

The study area comprises of five States and 95 Local Government Areas (LGAs) led by Governors and Local Government Area Chairmen respectively. The vulnerable areas as identified were classified based on their level of vulnerability, such as 'very much likely, very likely, less likely, unlikely, very unlikely, and very much unlikely. The percentages of the various levels of vulnerability show that areas very much likely to slide cover 2.68%, areas very likely to slide cover 13.50%, areas less likely to slide cover 1.57%, areas unlikely to slide cover 17.08%, while areas very much likely to slide cover 65.17% (Table 3, and Figures 6, 7 and 8).

Table 3: Landslide vulnerability and percentage area covered

S/No	Class of Vulnerability	Percentage Areas Covered
1	Very Much Likely	2.68
2	Very Likely	13.50
3	Less Likely	1.57
4	Unlikely	17.08
5	Very Much Unlikely	65.17



Fig, 7: Landslide vulnerability and percentage area covered

The model map allows for visualization of vulnerable and risk prone areas on the local levels, that is the localities closest to the vulnerability areas (Figures 6 and 8)

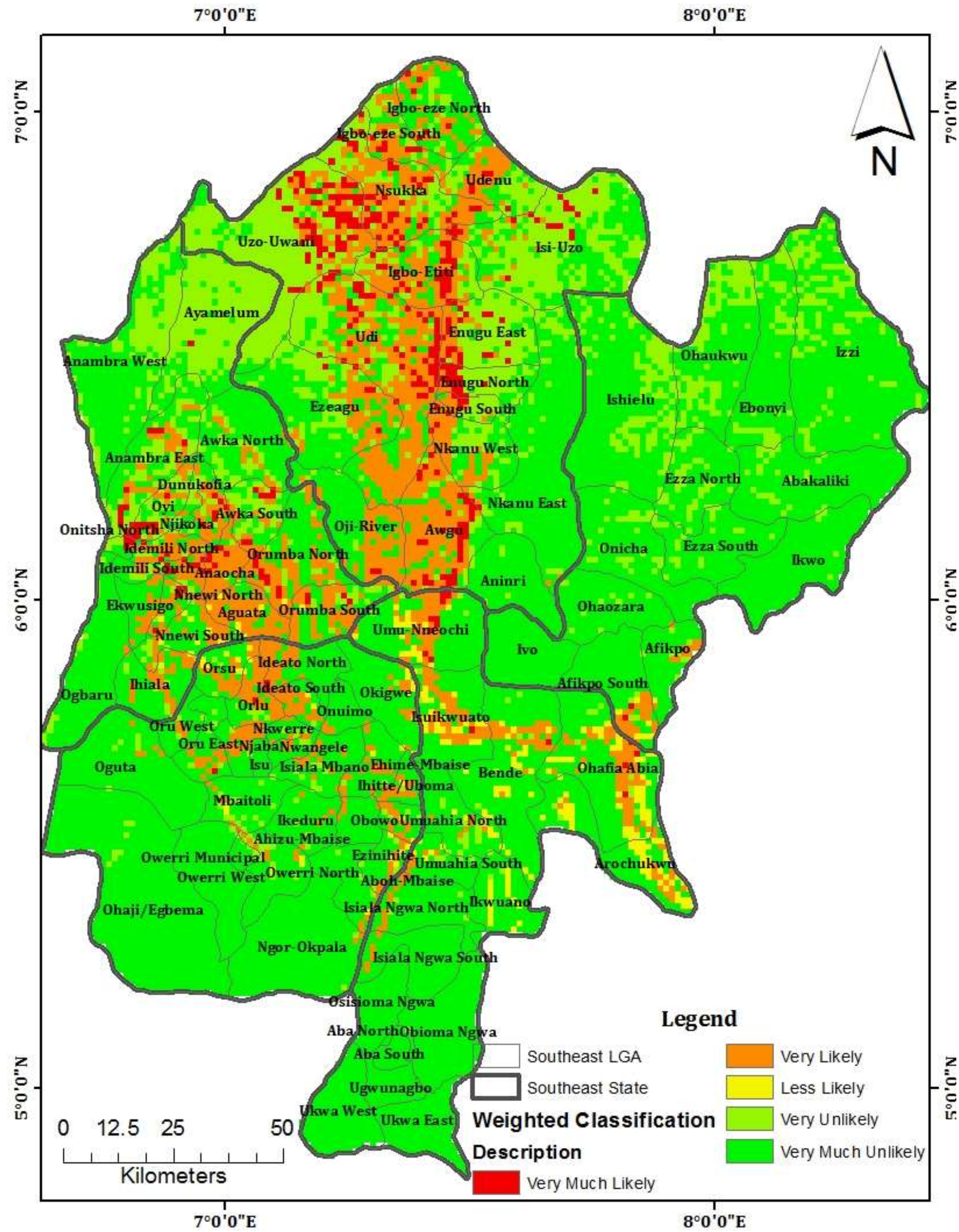


Fig. 8: Landslide vulnerability area in Southeast, Nigeria based on States and LGAs

6. Conclusion and Recommendations

Understanding the environment with the associated dangers posed by the terrain is a necessity that cannot be over emphasis if the risks of environmental hazards are to be reduced or averted completely. Landslides are environmental hazards that are meant to occur naturally as part of geomorphological processes. Natural hazards can become natural disaster if attention is not created, hence the need for this research in order to provide basis for guiding against. The study produced a model that shows all the landslide vulnerable areas in the study area that will serve as a guide to every other land related activities. As unguided development is spreading into the outskirts of the cities, it is important that caution is being taken to reduce creating landslide vulnerable areas as a result of stone cutting, sand mining and other anthropogenic activities capable of deforming the earth's surface that will eventually led to landslide. Landslide vulnerability assessment and mapping is very important and valuable, and serves as a needed guide for land use planning and monitoring in order to reducing landslides and the costs associated to it as posited by Fell et al (2008a) and Fell et al (2008b). The study recommended the use of laws to secure and regulate land use activities in the vulnerable areas, all encompassing involvement and commitment from stakeholders and managers of various governments at State and Local Government levels. Educating the inhabitants of vulnerable areas of the dangers associated with certain land use activities like indiscriminate and unguided mining of sand and stone and the need to avoid them, providing alternative means of livelihood that will discourage indiscriminate mining, deforestation, forest fire, and overgrazing, and encourage sustainable resource use and management that will not expose the areas to the triggering factors of landslide. Ensure revegetation (afforestation) of exposed vulnerable areas with grasses and medium sized tress to discourage runoff generation that may trigger landslide. Create a regional body vested with powers and resources to effectively monitor the environment.

Authors' contribution

Romanus Udegbunam Ayadiuno, Dominic Chukwuka Ndulue and Arinze Tagbo Mozie contributed to the research study conception and design. Material preparation, data collection and analysis were performed by Romanus Udegbunam Ayadiuno and Dominic Chukwuka Ndulue. The first draft of the manuscript was written by Dominic Chukwuka Ndulue; Romanus Udegbunam Ayadiuno commented on the draft versions of the manuscript. Romanus Udegbunam Ayadiuno and Dominic Chukwuka Ndulue read and approved the final manuscript.

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Availability of data and materials

The datasets used for the study are available from the corresponding author on reasonable request

Disclosure of potential conflicts of interest
The authors declared that there is no potential conflict of interests.

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