



Assessment of geospatial capability index for siting waste dump/landfill to control groundwater geopollution using geographic information system (GIS) approach: case study of Abakaliki area and environs, Southeastern Nigeria

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Abstract

Understanding spatial variation of rock and soil is important for capability precision as well as groundwater contamination or geopollution management. In view of waste dump/landfills, geoenvironmental hazards ravaging our land including surface and groundwater contamination, site suitability indexing, spatial distribution and characteristics of underlying rock and soil matter are studied. Rock and soil samples were collected in a systematic grid pattern using simple drill core rig and hand auger. Geostatistical and soil property analyses were conducted on each grid. Groundwater aquifer vulnerability to leachate was studied using depth to water table, recharge (precipitation), aquifer material, topographic slope, impact on vadose zone/vadose zone material and hydraulic conductivity (DRASTIC) and geophysical methods. Human population growth analysis indicates tremendous waste generation. Flash points of waste generation and dumping were noted. Geographical positioning system was used to take record of sampling point coordinates. Using a sufficient dataset, each grid indicative factor is objectively scaled, weighed and assigned a numerical rating according to their relative importance employing site suitability (S) analysis approach in an empirical equation. Results were imported into a geographic information system (GIS) platform to generate thematic maps. The results showed that subsurface rock and soil characteristics are neither spatially nor vertically homogeneously distributed. Thematic maps were generated and further interpolated in the GIS domain to produce a composite waste dump/landfill suitability index map.

Keywords Contamination · Geoenvironmental hazards · GIS · Spatial · Suitability · Variability · Waste dump

Introduction

Geology and soils are naturally never homogeneous; hence, there is growing interest in the study of geospatial variation properties of rock and soil using geostatistics since 1970s. This technique is yet well developed, but successful in characterizing the spatial variations of subsurface and soil (Liu et al. 2006). Many studies have been carried out on land capability index. Their results indicate diverse and dynamic system (Kavianpoor et al. 2012) changing their properties with time and space continuously (Maniyunda et al. 2013; Onwe et al. 2018). This heterogeneity in rock and soil properties is anisotropic across landscape. This inconsistency can be as a result of several interacting factors, their different intensities with different scales acting simultaneously (Serrano et al. 2014). Consequently, application of conventional land planning and allocation cannot overcome the issue of

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the inconsistency, resulting in mismatching when trying to assign capability to each of the many interests competing for an area of land. Severe environmental damage, deterioration and geohazards such as earthquake, structural failures, landslide and soil creep, including flooding, erosion, groundwater contamination/pollution arise due to land capability index mismatching (Onwe et al. 2018). Estimation of rock and soil properties' spatial variance is important for evaluating geoenvironmental resource vulnerability (Iñigo et al. 2012, Onwe et al. 2017). It provides the influential processes and factors controlling potential contamination and or pollution of groundwater resource (Akbas 2014). It is also an important determinant to water well as well as waste dump or landfill sitting, their design, yield efficiency and management.

The capability of an area for waste dump or landfill is a function of different parameters, including soil pH, soil organic matter, texture and biological activities as well as rock type and lineament including aquifer media characteristics (Karaca 2004; Onwe et al. 2017). Hence, determination of such parameters is important for evaluating geospatial capability index.

To facilitate development in line with sustainable development goals (SDGs), it is important to know the limitations of a land and the uses it is capable of supporting and how susceptible a land is to such factors as erosion and contamination influences. Nwankwor et al. (2004) and Onunkwo-A et al. (2011) determined geological parameters and used analytical manual overlay and GIS approach, respectively, to index land use. One important way to gather this knowledge is to undertake geostatistical and soil survey and prepare each factors' common georeferenced thematic map and through spatial integration by interpolation and simulation in a GIS platform. While some are small scale (Wilcke 2000), relatively few have been done at large scale (Qu et al. 2014). This study is undertaken in the research interest for analyzing the spatial variation and properties and identifying waste dump/landfill site probable or possible geohazard vulnerable zones for groundwater specific management using GIS platform.

Study area

This research was carried out in Abakaliki area, Southeastern Nigeria. It covers between latitudes 0389325–0444717 N and longitudes 0663306–0718503E, covering about 56.31 km². It has a highest altitude above the sea level of about 245 m (Fig. 1).

Climate and weather

The area is a tropical temperate and characterized by seasonal conditions caused by the North–South fluctuation of a discontinuity zone between the dry continental (Saharan) air and the humid maritime (Atlantic) air. This culminates in two main seasons dominating the area—rainy and dry seasons. Other minor climatic conditions in the area are the short dry season—August break and the harmattan patches of November to February. Mean annual rainfall is 2000 to 2500 mm and mean monthly rainfall varies from 50 to 300 mm, while mean annual temperature of 31.2 °C ranges from 33 °C in dry season to 28 °C in wet season. The area falls within the tropical rainforest to savannah belts with lush vegetation characterized by variety of tree shrubs, grasses and abundant palms (Onwe et al. 2015, 2016). Dominant vegetation is cereals (rice, maize), vegetables and fruits. The area consists predominantly of shale rock type. This weathers to lateritic clays, silts and clay soil deposits.

Materials and methods

Soil sampling and analysis

Using soil auger, soil samples were collected. Sampling points were selected in a systematic grid design using Mapsource. Each grid was specified at a fixed distance of 50 × 50 m² grid. Samples were collected at different locations at 1-m vertical interval in a total average depth of 0–15 m depending on soil thickness. Samples so collected were kept in a polythene container and sent to a laboratory within 48 h for analyses to evaluate the particle size distribution. The particle size distribution of the soil grading was done using an electric shaker machine. It was determined by passing a sample of the soil through a series of sieves and weighing the portions retained. The titration method using the K₂Cr₂O₇ was used to determine soil organic matter content. Casagrande apparatus was used to determine the Atterberg limit. To determine the optimum moisture content, compaction characteristics test and shear stress and compressive strength analysis were done. For laboratory analysis of natural moisture content of the aggregates, the modified drying method (BS 812: Part 2, 1975) was adopted. The natural moisture content of the aggregate was calculated using the relationship below:

$$\text{Moisture content (\% by dry mass)} = [(A-B)/B] \times 100 \quad (1)$$

where *A* denotes weight of aggregate before drying; *B* weight of the final oven-dried aggregate.

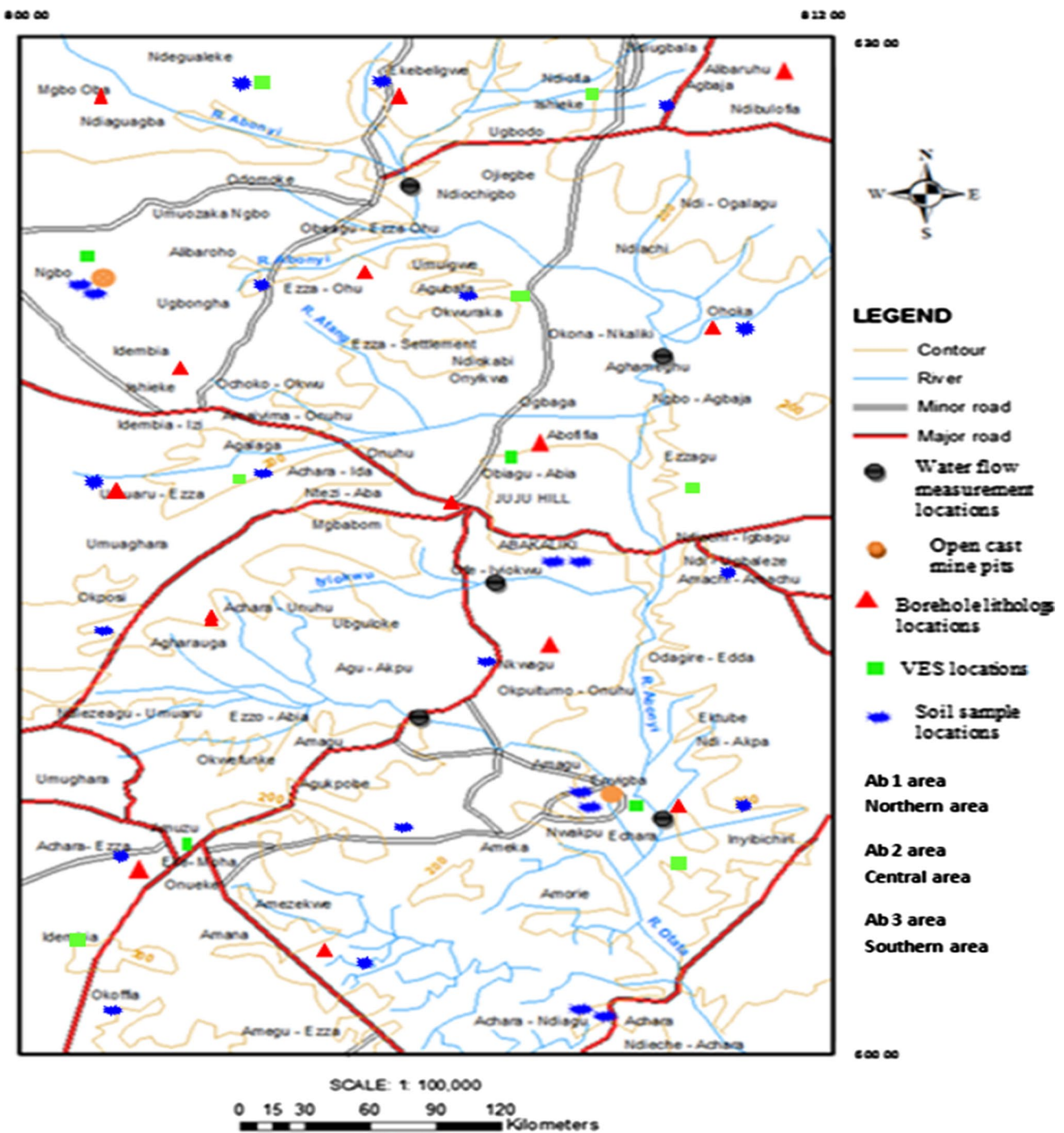


Fig. 1 Map of the study area. Source: Drafted from Map published by the Office of the Surveyor General of the Federation, Abuja Nigeria 2010; Sheets 302 and 303

Compressive strength test of residual soils determining the stress required to break a loaded sample that is unconfined at the sides was also examined. The compressive strength of soil depends on their porosity. Shear strength, the

resistance of soil/rock mass to shearing stress depending on the angle of internal friction, (ϕ), and cohesion, (c), between the particles of the materials were measured using direct shear test arrangement. They were studied with a view to

Table 1 The population data of the study area (population in thousands). *Source:* National Population Commission of Nigeria and National Bureau of Statistics web

1963	1971	1981	1982	1987	1991	2002	2006	2015
312.00	471.70	754.50	501.00	568.00	837.00	1217.00	13,402	4386.80

Table 2 Thematic map layers dataset for waste disposal land use option using geometry calculator to determine percentage influence

Input theme	% Influence	Input field	Input label	Scale value	Remarks
Layer 1	10	1	0–9 (gentle slope)	2	
Slope		2	>9–19 (sloppy)	1	Down-migration of leachate
		3	>19 (steep)	0	
Layer 2	6		Gradational		Used in the derivation of DEM for slope
Elevation			Discrete		
Layer 3	8	1	Abakaliki shale	1	Fractured. Enhances migration of leachate
Geology			Abakaliki pyroclasts		
Layer 4	10	1	Moderate	1	Poorly drained can lead to reducing condition
Drainage		2	Moderate	1	
		3	Well drained	2	
Layer 5	15	1	Very shallow	1	May be polluted when shallow. Difficult to exploit if deep
Water table		2	Shallow	1	
		3	Deep	2	
Layer 6	7	1	Buffered active	0	Reducing condition, distribution of waste and leachate. Buffer ≥ 1 km
Flood		2	Nonactive	0	
Layer 7	10	1	Buffered active	0	Can create pathway for leachate migration to groundwater
Fault		2	Nonactive	0	Buffer ≥ 1 km
Layer 8	18	1	Deep	2	
Soil depth		2	Deep	2	Attenuation of pollutants
		3	Shallow	1	
Layer 9	7	1	Ferric Acrisols	2	Based on percentage of fines
Soil class		2	Dystric Nitosols	1	Ferric Acrisols—20
		3	Gleysols	0	Dystric Nitosols—30 Gleysols—50
Layer 10	8				
Hydrology			Buffered		≥ 1 km
Total					

understand the engineering and attenuation characteristics. Information on soil class/type, depth and texture (porosity) was obtained.

Geostatistical study

Core drilling, vertical electrical sounding (VES) and profiling were used to undertake surface and subsurface spatial geostatistical studies. Measurements on lineaments (fracture) orientation, aperture, trace length and spacing were taken with the aid of Garmin 78sc geographical positioning system (GPS), callipers, tape and Brunton compass. Their geospatial analyses were carried out employing geostatistical/geospatial mapping

software (ArcGIS, Global mapper, Rockworks 16). The spatial variability parameters were calculated in numerical value, and interpolation was performed in ArcView GIS 10.2.

Hydrology and drainage

Water table approximate static level elevation and DRASTIC analysis were employed to understand aquifer vulnerability to contamination and possible pollution of the groundwater. Drainage network, patterns and regime were assessed to enable the determination of channel geometry (depth, width and mean flow velocity) and flood incursion risk area and scenario.

Population

Considerations under this factor include population size, characteristics and projections. According to the National Population Commission of Nigeria and National Bureau of Statistics web, the population of Abakaliki area and environs is presented in Table 1.

Using the population data, the growth rate from 2006 to 2015 is 15.31%/year. Based on this growth rate, a projection to the year 2020 is forecasted.

Waste disposal siting criteria

Wastes are worthless, unwanted, defective or of no other value substance which constitutes a scrap, (U.S. EPA 1990; Oyediran 1997). It could be toxic and has the potential to defect other substance. Site evaluation for waste disposal involves a basic understanding of soil and subsurface properties and the treatment and limitations of the waste mechanisms polluting groundwater or loading rate. Sites are selected after a reconnaissance survey of an area. The criteria checklist includes population, climate, geology, lineament, soil class, soil depth,

Fig. 2 Schematic overlay model for waste disposal land use

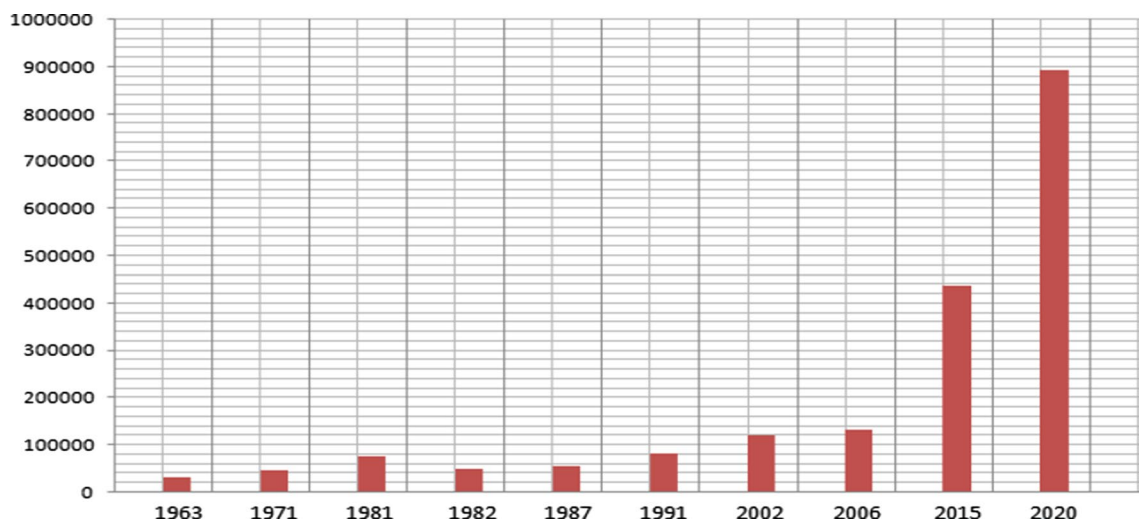
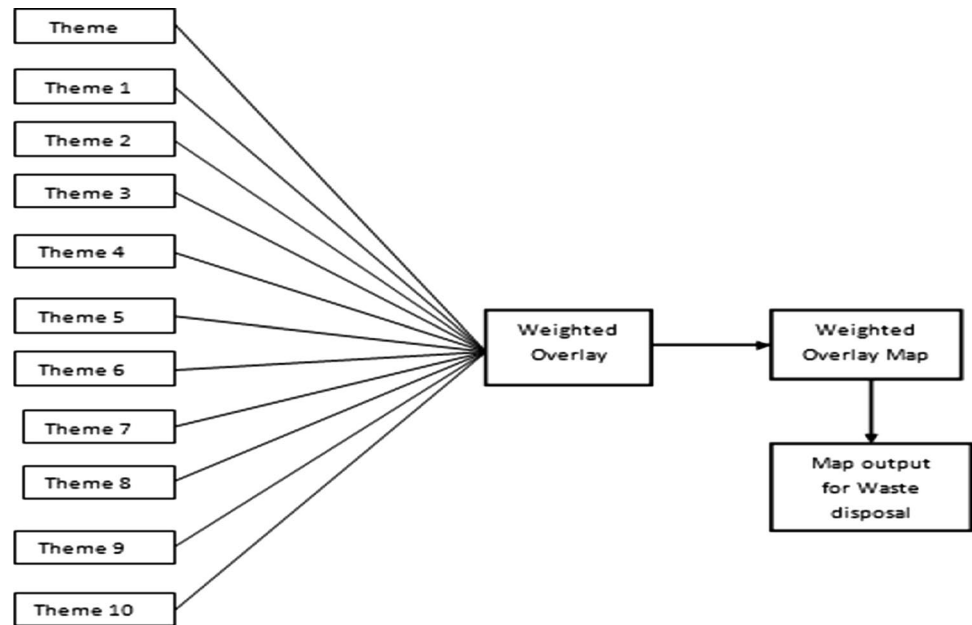


Fig. 3 Year 2020 projection of Abakaliki population using National Population Commission of Nigeria, and National Bureau of Statistics population data

Table 3 Results of the soil properties of Abakaliki area and environs

Parameter	Western region	Northeastern area	South-eastern area	Central region	North-western area	North/South area	South-western area	Range	Average
Specific gravity, Gs	2.54	2.56	2.64	2.6	2.45	2.6	2.54	2.45–2.64	2.56
Bulk density	1.55	1.68	1.52	1.45	1.57	1.59	1.45	1.45–1.68	1.54
Plastic limit, PL (%)	24.8	24.6	25.3	27.4	27.2	28.1	23.2	23.2–28.1	25.8
Liquid limit, LL (%)	66	58.8	62.4	72.8	62	56	60	56–72.8	62.57
Plasticity index, PI	41.2	44.2	43.4	45.8	39.5	46	42.1	39.5–46	37.37
Activity	1.21	1.16	0.9	1.09	0.85	0.63	0.84	0.63–1.21	0.95
Natural moisture content, %	21	23	20	24	21	19	22	19–24	21.43
Maximum dry density, MDD (mg/m ³)			1.83	1.88	1.89	1.87	1.86	1.85–1.89	1.87
Optimum moisture content, OMC (%)	12.1	12.0	12.5	12.3	12.2	12.4	12.1	12.0–12.5	12.2
California bearing capacity, ^a CBRu (%)	22	21	22	21	23	22	22	21–23	21.7
California bearing capacity, ^b CBRs (%)	11	10	12	10	13	12	11	10–13	11.28
Shearing angle resistance, ϕ (°)	23	30	31	28	32	31	25	23–32	28.57
Cohesion, c (kN/m ²)	50	55	54	55	53	54	52	50–55	53.28
Density (g/m ³)	2.29	2.28	2.33	2.30	2.27	2.28	2.28	2.27–2.33	2.29
Porosity (%)	10.6	10.99	9.03	11.02	11	10.9	10.64	9.03–10.99	10.59
CEC (milli equiv.)	9.26	8.89	9.51	9.02	9.30	9.40	8.98	8.89–9.51	9.19

Atterberg limit test, specific gravity, bulk density and calculated activity value

^aUnsoaked condition, ^bsoaked (24-h soaking) condition

Table 4 Particle size distribution at different areas

Area	Depth (cm)	% sand	% silt	% clay	Texture	Difference
Northern area	0–15	21	28	49	Silty clay	Little plasticity. Cohesive. Porous but little permeability. Limited ability to retain organic nutrient. Offers the good potential for waste renovation and application
	15–30	29	23	46	Sandy clay	
Mid-central	0–15	26	22	51	Sandy clay	Porous, permeable, low cohesion and plasticity. Poor retention of water. Well-drained soils offer the greatest potential for waste renovation and application
	15–30	23	21	55	Clay	
Southern area	0–15	19	20	60	Clay	Most plastic and cohesive of all. Good attenuation medium. Ability to retain more plant nutrients. Poor engineering property
	15–30	16	18	63	Clay	

topographic/elevation, slope, water table, hydrology, land use, drainage characteristics and flood incursion scenario.

In considering waste dump site, shallow spelt groundwater table, recharge and discharge areas should be avoided. Proximity to streams or lakes causes runoff contamination and pollution including groundwater, wells and aquifers. Sites closer than 100 m to a high-yield well may be excluded.

Prolonged wet period impairs waste renovation, affects aeration and causes the likelihood of increased surface runoff. Topography informs the nature of slope. Slopes > 15% are considered too steep and not good for waste disposal land use.

Medium-textured soils ranging from sandy loams to silty clay loams are generally suitable. The actual thickness of material above a permanent water table, bedrock or some other restricting layer constitutes the effective depth of soil useful in the renovation of waste; at least 3.05 m of permeable, unconsolidated material above a water table is generally recommended (Raymond 1979). Poorly drained terrains are not very suitable for waste disposal. Well-drained soils offer the greatest potential for waste renovation and application. An insufficient volume of well-aerated material reduces the soil's ability to purify effluent. Carbonate rocks, fractured rocks and permeable rocks

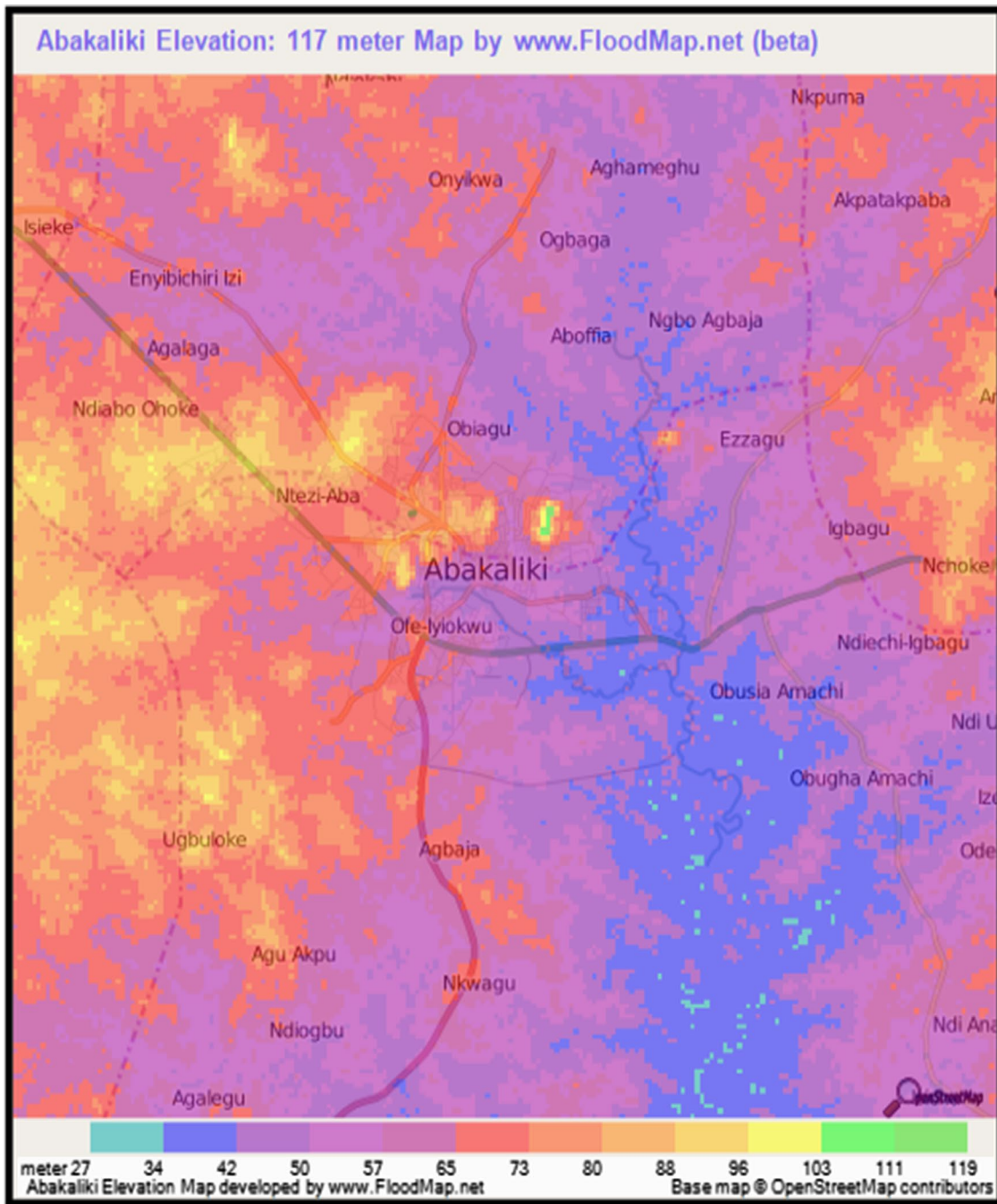


Fig. 4 Flood incursion map of study area generated using Google Earth

form solution channels and are susceptible to solution and facilitate leachate fluid migration. These affect stability and potential release of pollutants. Higher-cation-exchange-capability (CEC) areas are preferable waste disposal sites.

Exploratory statistical analysis

Geostatistical parameters accepted as indicators of the central tendency and spread of the data were analyzed. The

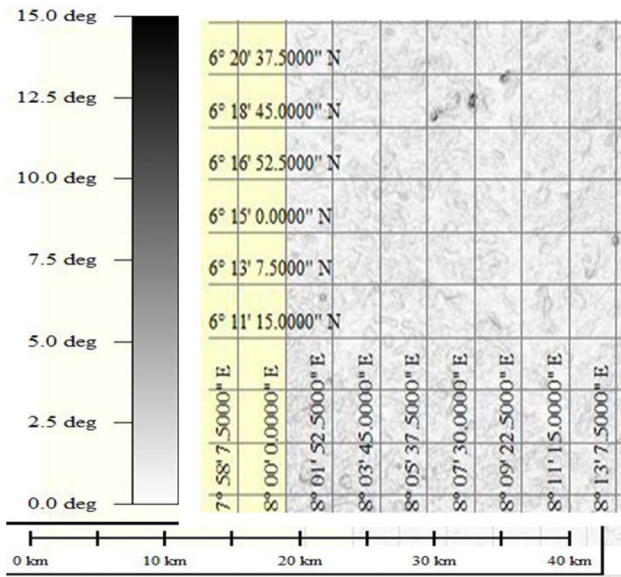


Fig. 5 Relief map of the study area

distribution of the geostatistical data has an important implication on the analysis result. Using a sufficient dataset, each grid was objectively scaled, weighed and assigned a numerical rating according to their relative importance. Various softwares such as Microsoft excel, Mapsource mapper, ArcGIS, Rockworks 16 were used to generate population projection and thematic maps accordingly. The different shapefiles or thematic layers of geology, geostructure (lineament/fault), physiography (topography, elevation and slope), groundwater depth, drainage pattern and density, flood incursion scenario, soil (types and depths) including land use and sensitive population hotspots maps and other soil geotechnical characteristics were generated. They are the geosurvey baseline information dataset used for this study and using the generalized site suitability (S) analysis approach form as follows:

$$S = \sum_{j=1}^n c_j x_j \quad (2)$$

where x_j are the factors affecting suitability; c_j are characteristic feature attributes of x_j .

Using a sufficient dataset, the c_j s are objectively scaled, weighed and assigned a numerical rating according to their relative importance, Saaty (1980) applied. The percentage influence values were obtained through weighted cells suitability or their relative importance reclassification of the thematic maps to a common measurement scale overlay tool. The tool ensures spatial connectivity of the cells and

performs the analysis on discrete neighborhood cell using the Majority filter tool. The output cells generated were converted to polygon where the area for each polygon was determined using the geometry calculator. Table 2 lists the characteristic feature rating of waste disposal site factors.

Dumpsite descriptive statistics

- Site should be in an area of mild slope, not water logged.
- Site should be in an area moderately shallow or deep water table.
- NOT near water catchments area, surface water and other sources of fresh water.
- Sandy clay environment is preferably better.
- Site should not be in an active fault, landslide or flood incursion, seismic zones and unstable areas like swamps.
- Site should be at a threshold distance of 1 km from major streams and not nearer than 200 m to populated areas.
- The site shall not be 3–5 km nearer to the airport area.
- Site shall not be in a highly permeable soil areas.
- May be close to an agricultural land use area, mainly a small-scale farming.
- Difficult long hauling distances (≥ 5 km) access from main roads to the surroundings of the site and to the site itself should not be a site.
- Site should not be too little available volume.

The various datasets obtained were integrated in an equal georeferenced GIS window to produce thematic maps. The thematic maps generated were further interpolated using ArcGIS software. The procedural overlay model is shown in Fig. 2 and when processed produces a waste disposal land use map.

Results and discussion

Based on the growth rate, a projection to the year 2020 is forecasted (Fig. 3).

Population results show that there would be tremendous needs for housing, high waste generation and probable over withdrawal of groundwater. The descriptive statistics of the parameters are given in Table 2. Soil analysis of the study area and environs as conducted is given in Table 3.

Zonal particle size distribution of soil grading as done using an electric shaker machine is summarized in Table 4.

Result of flood incursion threshold map was developed using the Google Earth (Fig. 4).

The flood incursion map was then imported into ArcGIS software for spatial analyses. Slope thematic map was

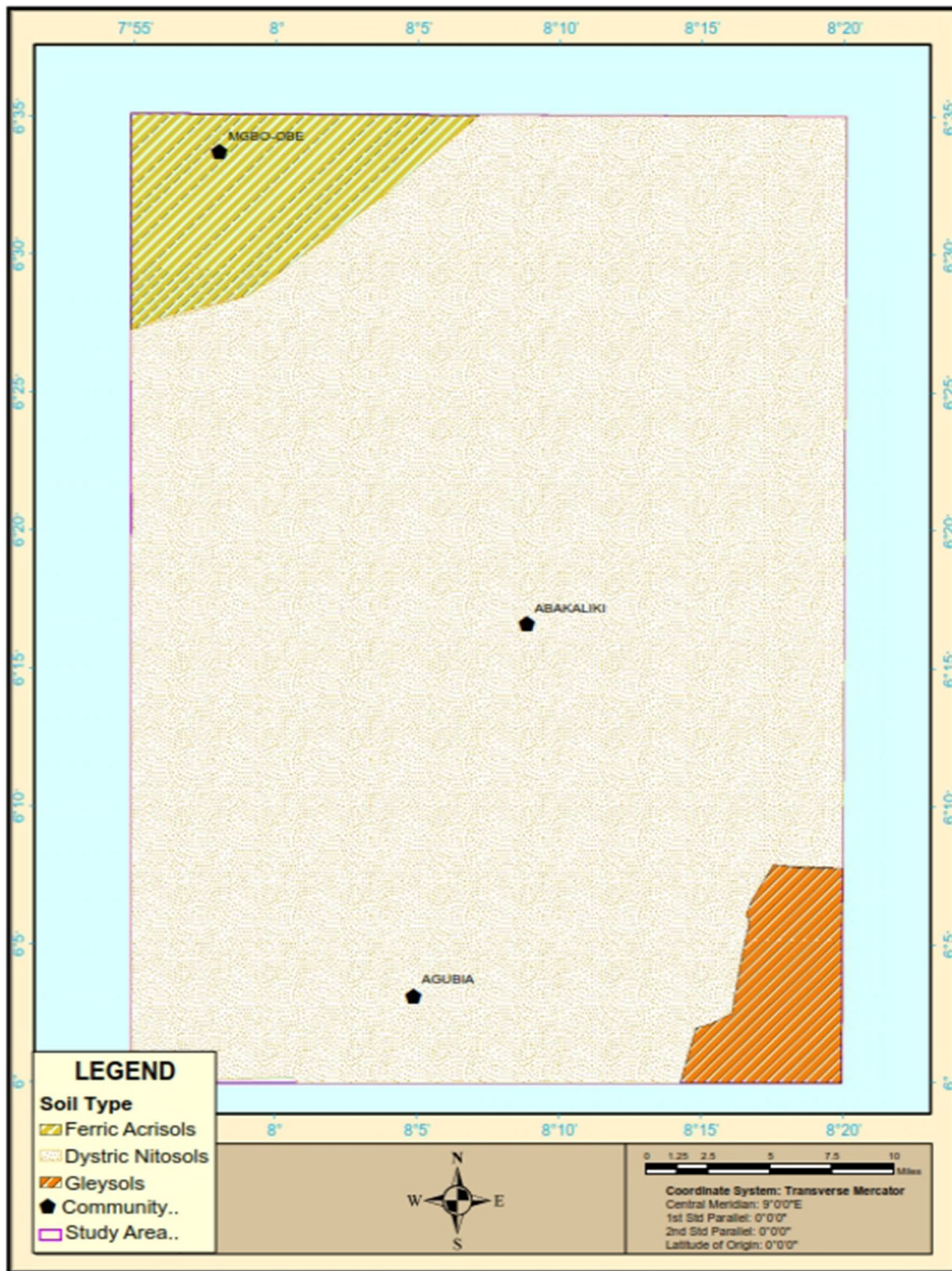


Fig. 6 Soil type map of the stud area

generated from digital elevation model (DEM). The DEM was converted to raster data format before being used for spatial analysis. The presence of factors can significantly increase the vulnerability of the groundwater aquifer. GIS

techniques have been used to present the spatial range of the areas with different levels of risk for increased vulnerability, together with data on the spatial range of its groundwater vulnerability.

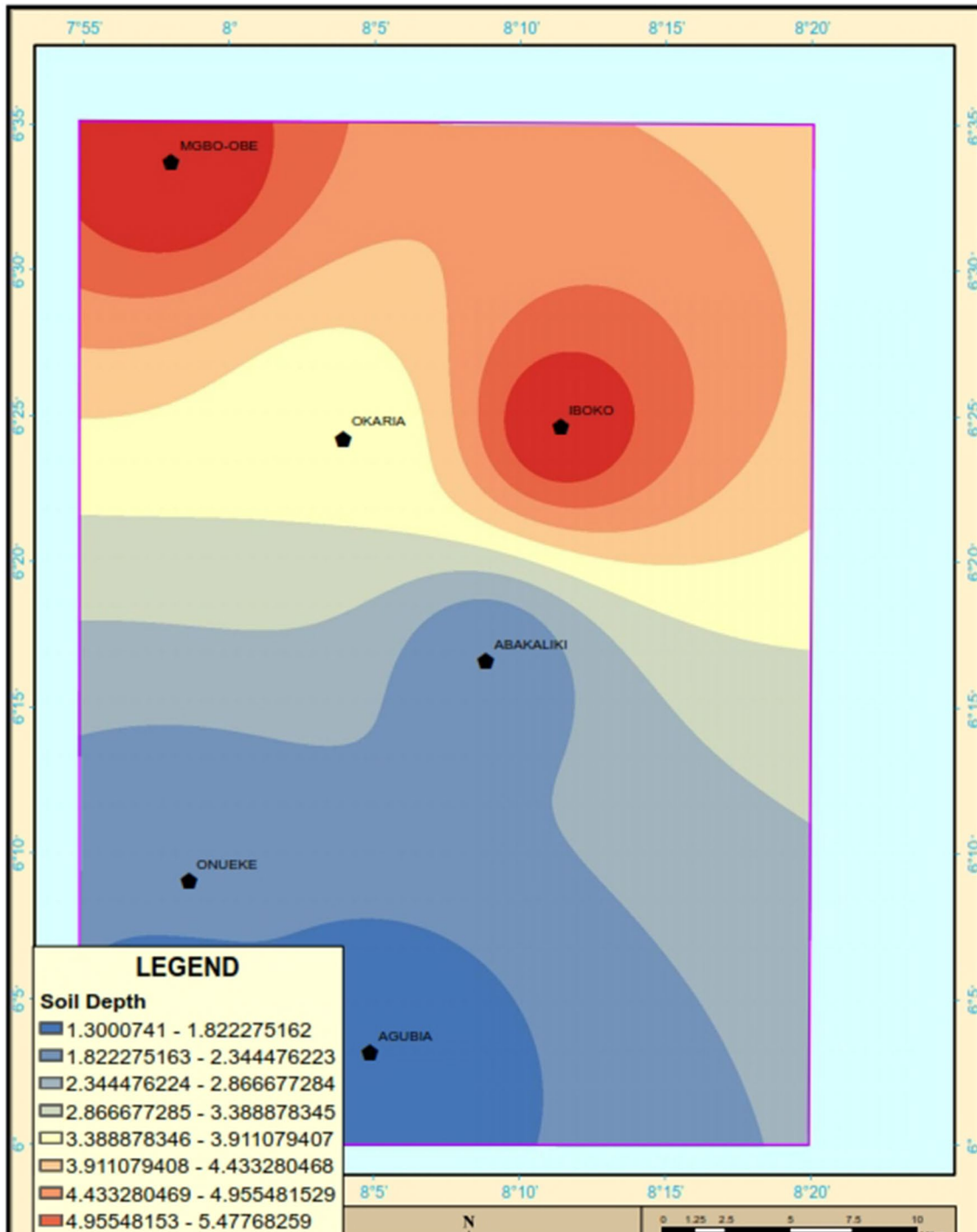


Fig. 7 Soil depth map of the study area. Depth range in meters

Thematic maps of all other factors are shown in Figs. 5, 6, 7, 8, 9, 10, 11 and 12.

$$\text{Using } \sqrt{[\Sigma(x - \bar{a})^2/n]} \tag{3}$$

where x is set of n values, \bar{a} is mean of x , the standard deviation, ϕ , is calculated. Substituting 9.0179 for x , 0.11133 for

\bar{a} and 81 for n , ϕ of the fracture size frequency distribution is 0.9896 (Fig. 13).

The Rose diagrams (Figs. 14, 15, 16 and 17) indicate probable conduits flow part direction in some parts of the study area.

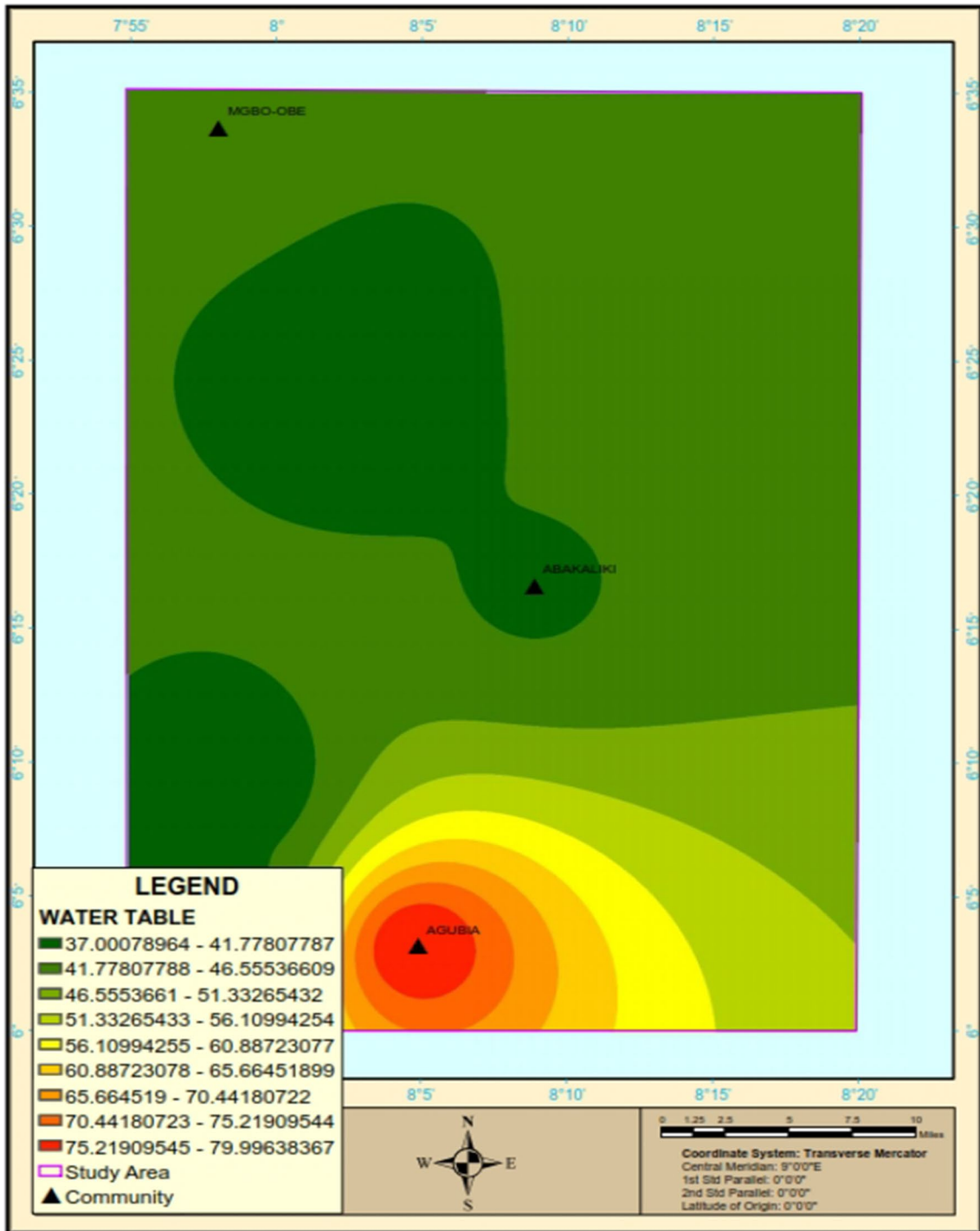


Fig. 8 Water table map of the area. Depth range in meters

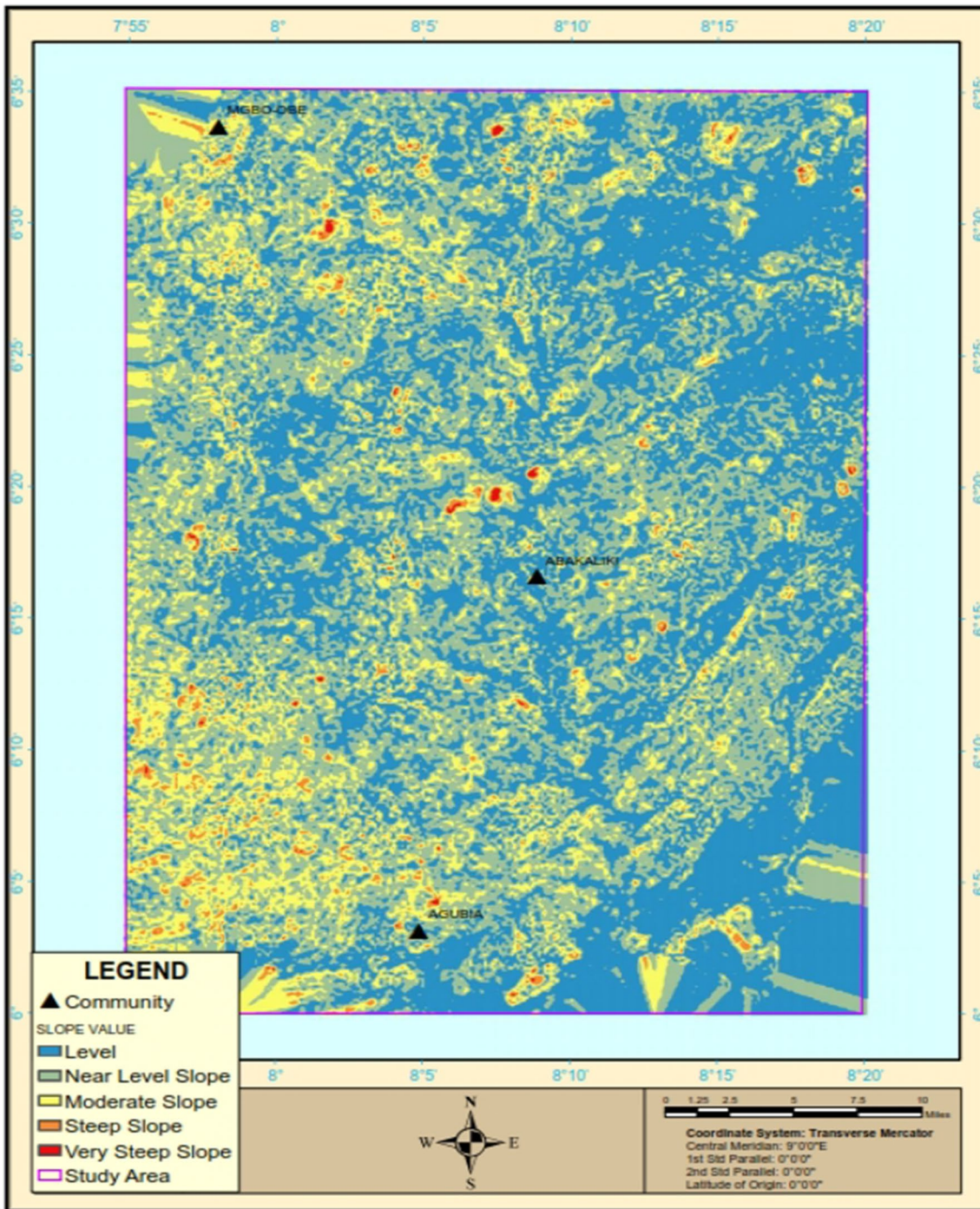


Fig. 9 Slope map of the study area

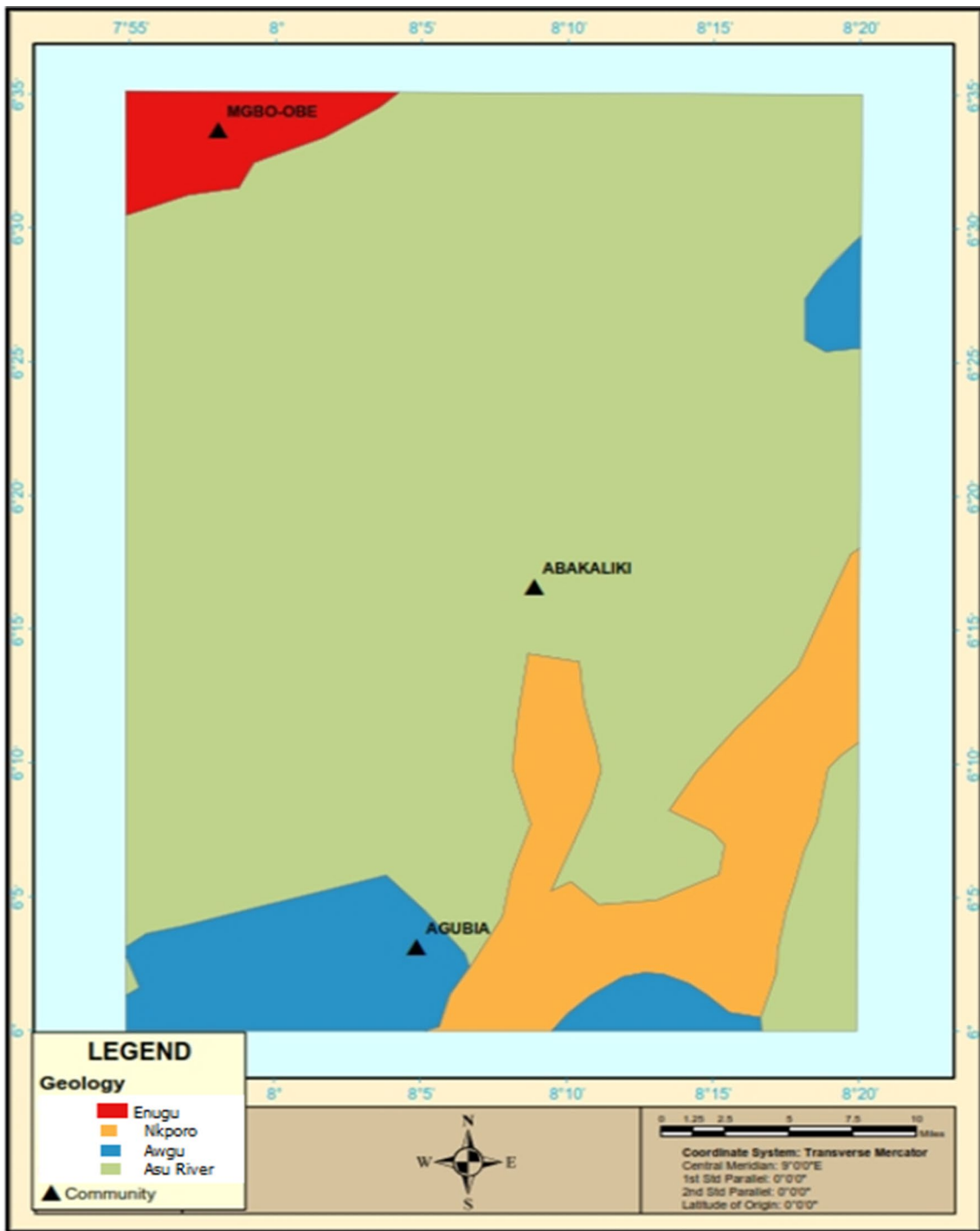


Fig. 10 Geology map of the study area. Adapted from Nigerian Geological Survey map, sheet 302

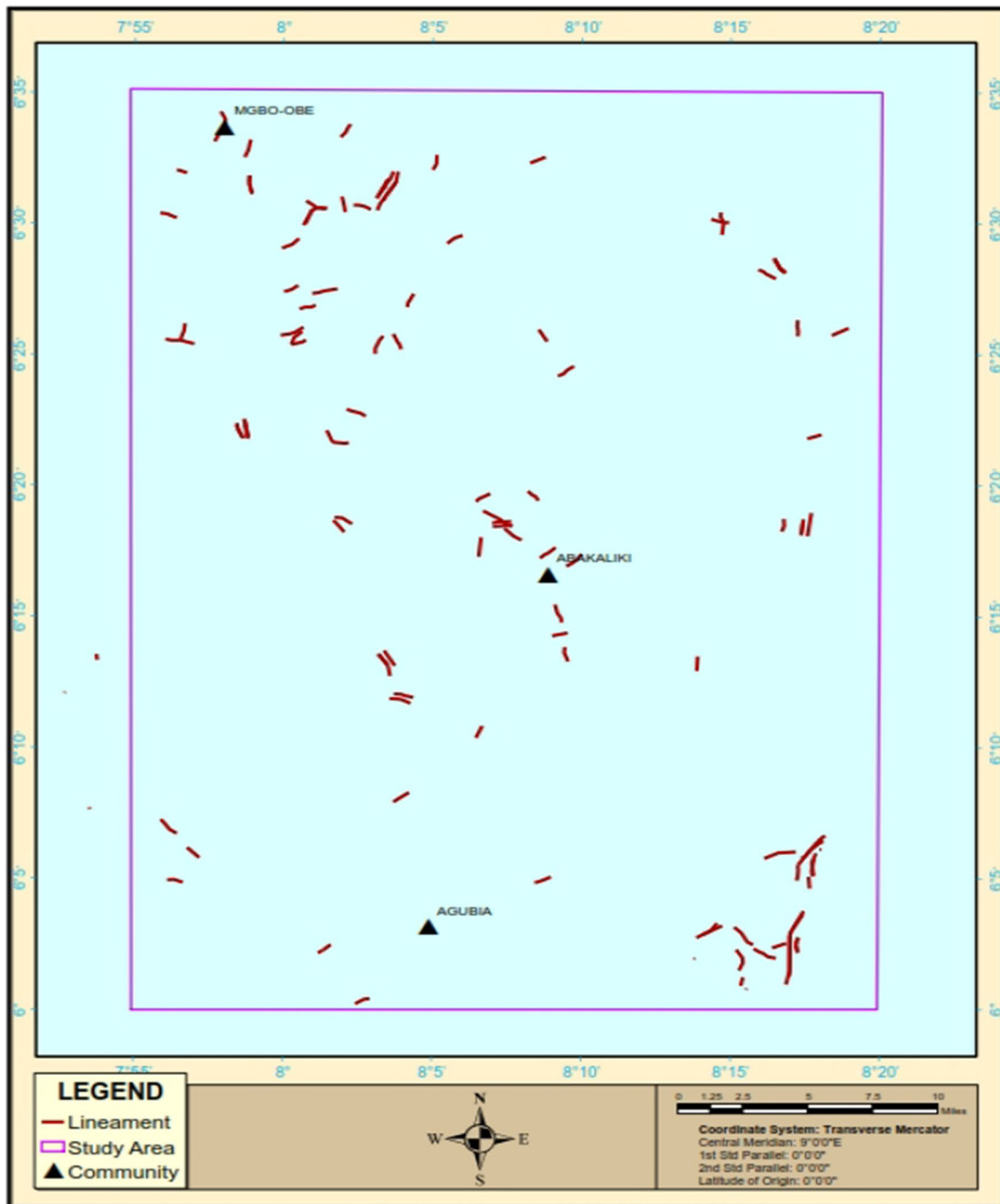


Fig. 11 Linearment density map of the study area

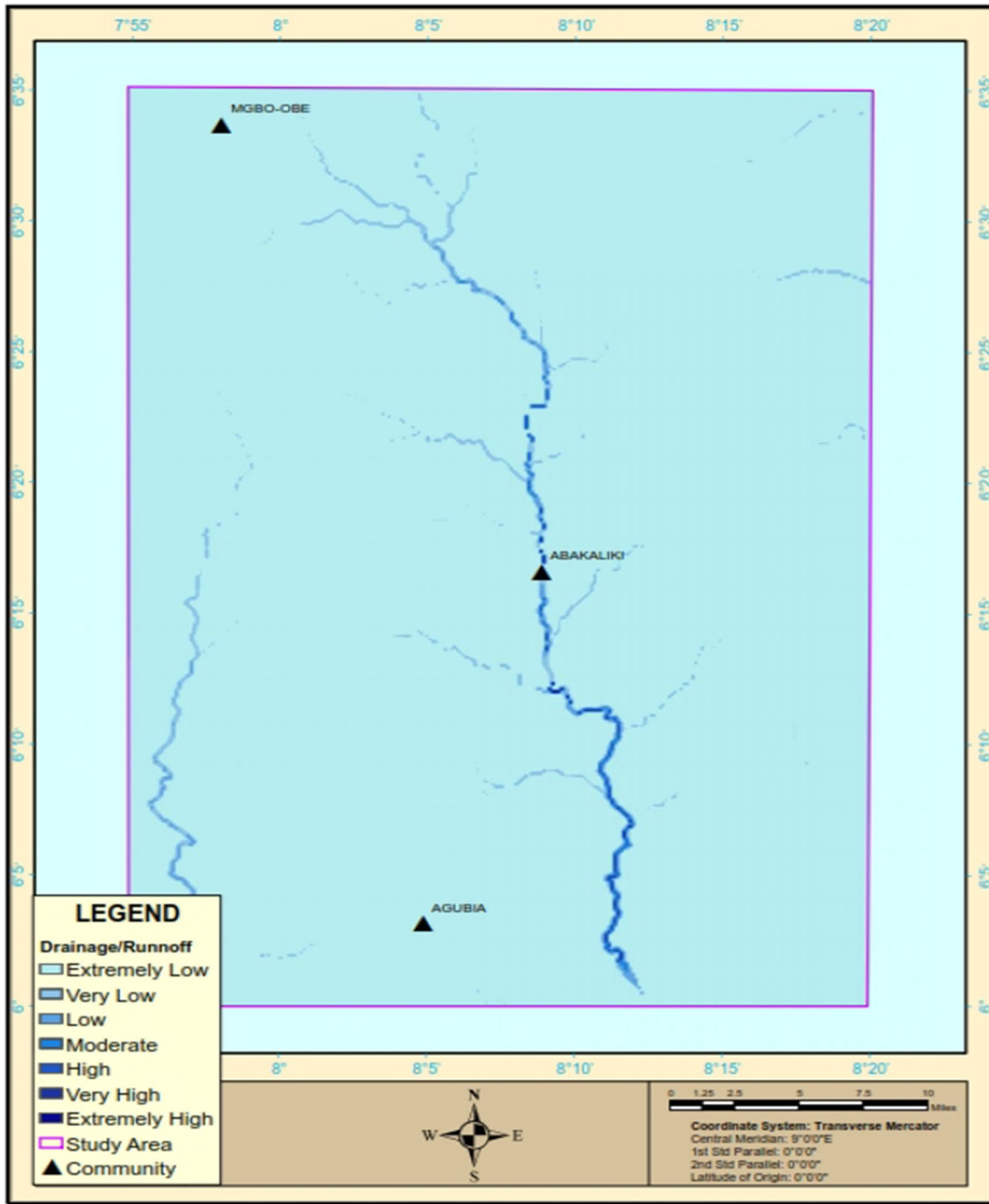


Fig. 12 Drainage map of the study area

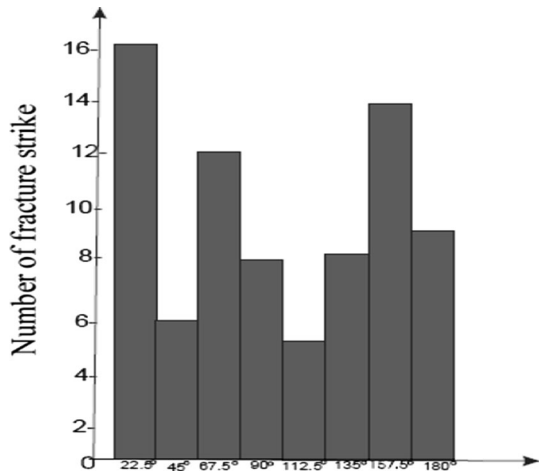


Fig. 13 The histogram of the plots of fracture strike azimuthal frequency distribution

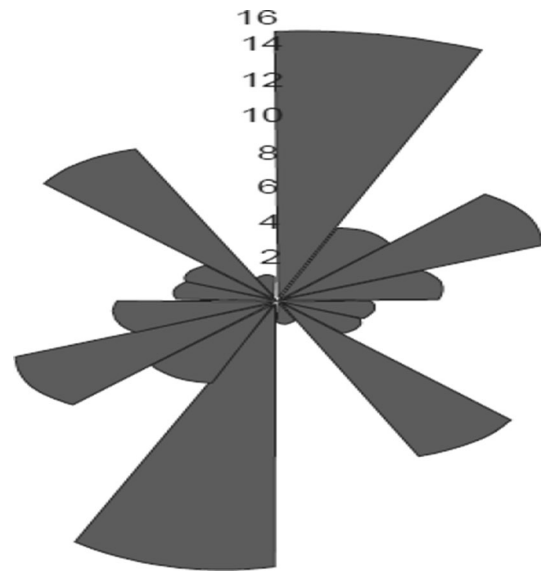


Fig. 15 Polar plot of fracture orientations in northern parts the study area

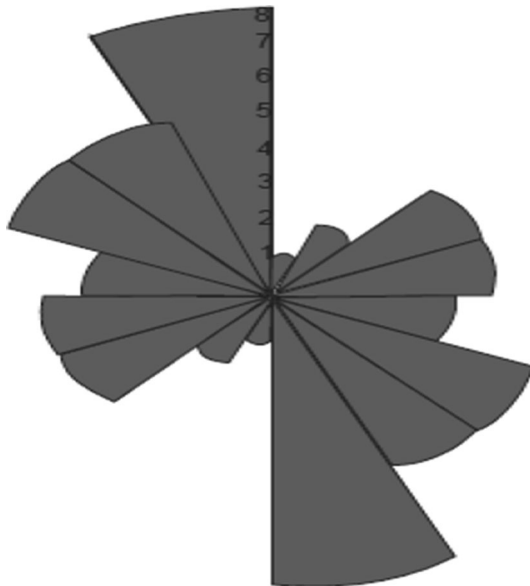


Fig. 14 The distribution of fracture strike with azimuth

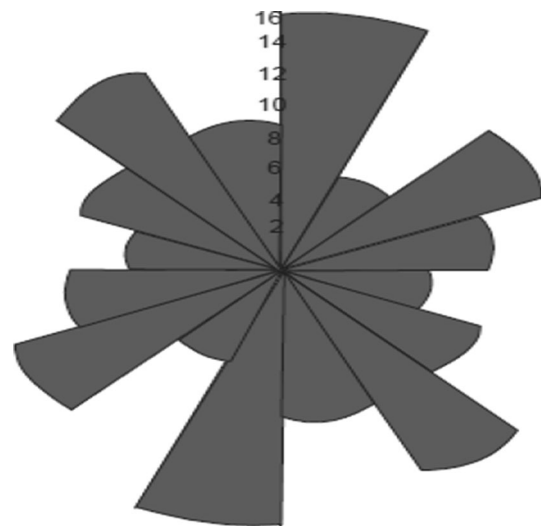


Fig. 16 Polar plot of fracture orientations in southern parts of the study area

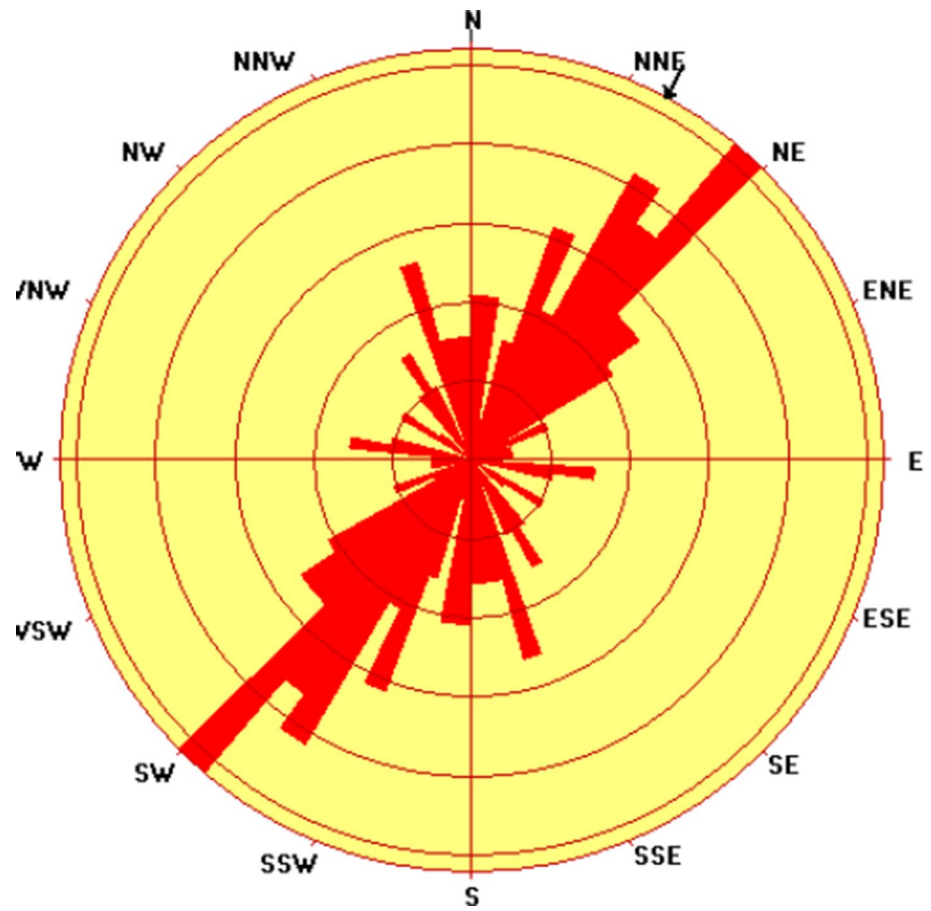
The result of a GIS spatial analysis performed using ArcView Model Builder operation produced unsuitability, low suitability and suitable options (Fig. 18).

Discussion

The predominant shale in the area has favoured the low erodability of the lithology, resulting in the absence or near absence of deep and steep cut slopes, valleys and erosion

channels but thick clayey top horizon. The areas' shale formation and considerable clayey soil thickness with high percentage of fines form groundwater protector and ensure waste dump/landfill suitability having attenuation and renovation potential for waste Leachate especially to the North-eastern region of the study area. Its suitability for waste disposal sites is not without concern due to the geostructural or lineament implication which serves as a leachate conduit and

Fig. 17 Composite lineaments azimuthal frequency direction



needs consideration. The entire area is highly fractured, and composite Rose diagram indicates a NE–SW orientation. The presence of fractures and faulted formations contributes to low or unsuitability. Its conduit permits possible infiltration of leachates into groundwater.

Results indicate soil cover is thicker toward the northern part of the area, while shallower toward the southern part. This suggests groundwater may be more vulnerable to contamination toward the southern region. This may be further worsened with lineament and drainage flow direction, generally NE–SW and N–S, respectively. The unsuitable areas for waste dump correspond to the area around the Juju hill which has a fairly steep slope. Unsuitable areas further fall mainly around major drainage channels and flood-vulnerable

areas measuring about 0.5–1 km from major rivers, streams and tributaries.

Waste dump/landfill suitable area falls around the uppermost northeast and a marginal portion in the southwest of the study area corresponding to area of thick soil cover. The northeastern region suitable for waste dump option falls within the sandy clay with reasonable soil and water table depth thickness ranging between 3.9–5.4 m and 41.7–46.5 m, respectively. Some other parts with higher soil or water table thickness that would have been suitable for waste dump option are knocked off or nullified by other characteristics such as soil texture, geostrophical effects, drainage and flood scenario. The area not suitable for waste dump/landfill purposes may be suitable for other options not considered in this research.

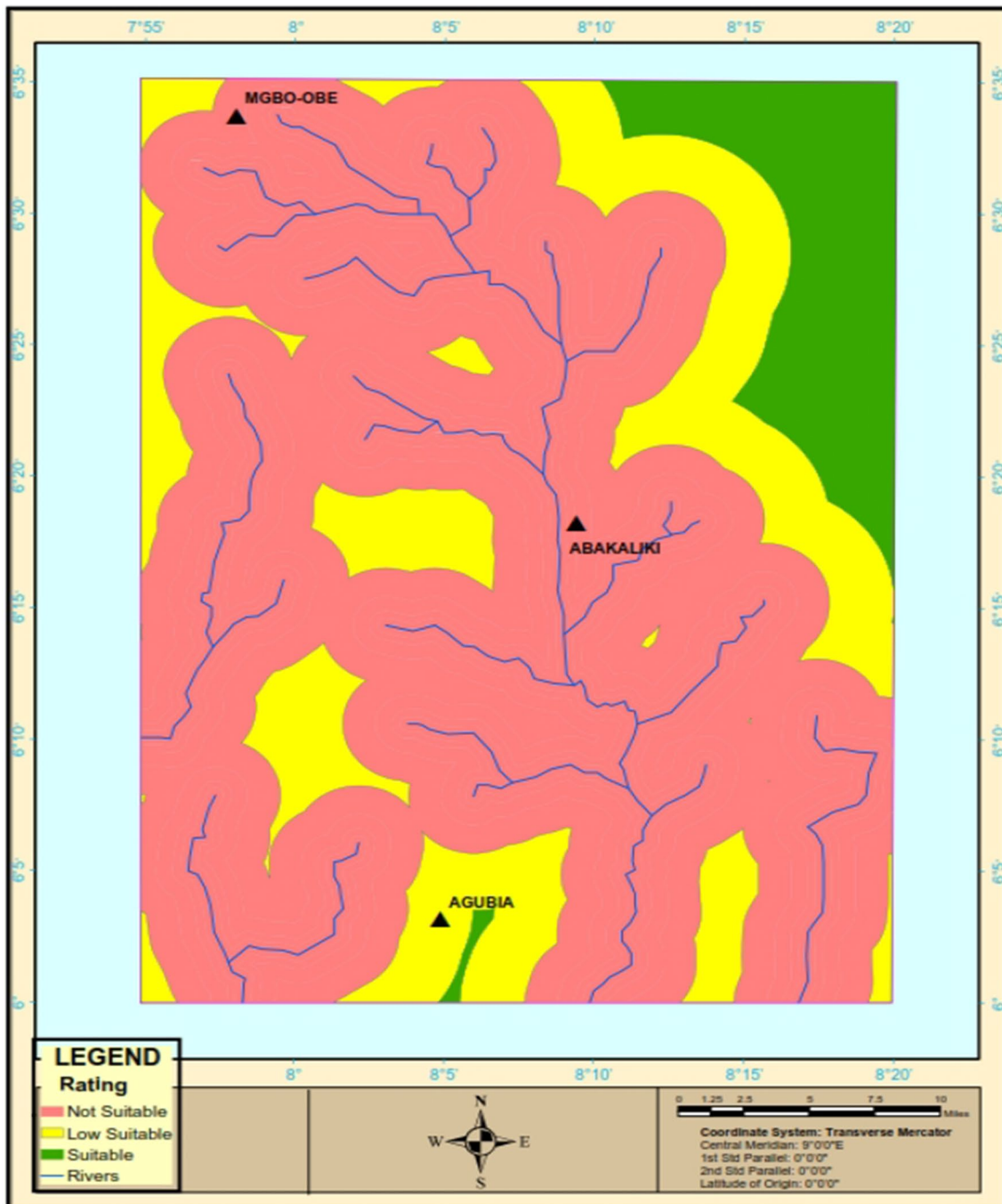


Fig. 18 Composite land capability index map for waste disposal of the study area

Summary and conclusion

In view of increasing depletion in groundwater resources mainly because of excessive mismatch in waste dump/landfill sitting, a GIS-based approach to estimate spatial distribution of soil and subsurface rock properties to delineate potential areas is pertinent. Result show that human

population density, drainage pattern and flow direction, flood-vulnerable areas, depth to groundwater, soil texture, rock type, geostructural features (faults, fractures) and slope nature are consideration factors in sitting waste dump/landfill especially to checkmate groundwater contamination and possible pollution.

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