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Spaceborne Fracture Network Mapping for Appraising Slope Stability, Building Structural Integrity and Groundwater Potential Distribution in Lokoja, Nigeria

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Abstract: *Fracture mapping has been traditionally conducted from field geological studies but this has the limitation of covering only a small area and many fractures are missed in the process. The use of satellite images to extract lineaments that represent structural deformations can adequately compliment the tedious and time-consuming field mapping. The main objective of this research therefore is to produce a fracture network map (structural map) of the study area from satellite images (Sentinel-2A). Other objectives are to (1) assess the structural stability of hilly/mountainous areas currently faced with development pressure through the production of terrain stability map (2) assess current buildings structural integrity through the analysis of building deformity and (3) produce a city-wide groundwater potential map through analyses of lineament densities and slope gradients. Automatic lineament extraction identified 13 lineaments predominantly trending NE–SW, with higher densities around the southern and northeastern parts of the area. Slope analysis revealed steep gradients along the northern fringes associated with the Mount Patti ridge, while the remaining areas exhibited generally gentle slopes. Combining lineament density and slope data enabled the delineation of stable and unstable terrain for development. A structural assessment of 240 buildings indicated that most buildings with and without defects are located within the stable terrain, suggesting that additional factors such as construction quality may be influential. Groundwater potential mapping revealed high-potential zones in the southern, eastern, and northeastern areas where high lineament density coincides with low slope gradients. Validation using eleven boreholes yielded an accuracy of 64%, confirming the reliability of the integrated approach. Overall, the study demonstrates the effectiveness of combining multispectral remote sensing and GIS-based analysis for evaluating geomorphological hazards, supporting informed urban planning, and guiding groundwater resource development in Lokoja.*

Keywords*: Lineament Mapping; Slope Stability; Building Integrity; Groundwater Potential; Remote Sensing; Lokoja, Nigeria*

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1.0 Introduction

Fractures, often expressed as lineaments, can be effectively mapped either manually or automatically using spaceborne satellite imageries, especially after applying appropriate filtering and enhancement techniques. This method is not only rapid but also yields better results compared to conventional field mapping (Wajid et al., 2021; Skaknia et al., 2021).

The significance of fractures in geosciences cannot be overstated. Accurately identifying fractures is essential for the exploration of both renewable and non-renewable resources, such as solid minerals, groundwater, hydrocarbons, and geothermal reservoirs (Jimoh et al., 2023; Ahmed II et al., 2022; Enoch et al., 2021), which are critical to national development and economic prosperity.

Lineaments represent the surface expressions of subsurface structural features, including joints, faults, and fractures, typically formed through tectonic deformation (Salawu et al., 2021). However, lineaments identified from satellite imagery may also correspond to geomorphological features such as linear valleys, cliffs, and terraces or arise from tonal contrasts related to rock composition, soil moisture, or vegetation cover (Ahmed II et al., 2019). Therefore, lineament analysis also provides valuable insights into various environmental phenomena, including crustal movements, slope stability, and other related geohazards (Hu et al., 2019).

A wide variety of satellite imageries acquired both in passive and active modes are available for lineament extraction. Studies have demonstrated that different image sources can yield significantly different results in terms of lineament distribution, length, and density (e.g. Adiri et al., 2017; Céleste et al., 2021; Xu et al., 2022). In a comparative study of four optical satellite datasets for the Lokoja region, Ahmed II et al. (2024), established that Sentinel-2A outperformed Landsat-8 OLI/TIRS, ASTER multispectral, and ASTER-DEM in terms of extraction accuracy. The study further concluded that the reliability of lineament mapping is influenced not only by the quality of the imagery but also by the geological and geomorphological characteristics of the study area highlighting that no single dataset is universally optimal.

Despite several studies demonstrating the usefulness of satellite imagery for fracture and lineament analysis, research in the Lokoja region has largely focused on identifying lineament patterns without integrating their implications for geomorphological risks and resource distribution. Previous comparative work has evaluated different datasets for lineament extraction accuracy; however, there remains no comprehensive study that combines fracture network mapping with slope stability assessment, building structural integrity analysis, and groundwater potential evaluation using Sentinel-2A imagery. This integrated approach is essential for understanding how subsurface structural features influence terrain stability, settlement safety, and groundwater availability in Lokoja.

In the light of these findings, this study employs Sentinel-2A imagery to extract lineaments with the aim of assessing their influence on slope stability, building structural integrity, and groundwater distribution within Lokoja, Nigeria.

1.1 Description of Study Area

The study is centered within the city of Lokoja, Nigeria, where it is geographically located between latitudes N7°46'58" – N7°49'03" and Longitudes E6°41'35" – E6°45'00", covering an area of about 14.7km^2 (Fig. 1). The city has an undulating topography with elevations that range from 100m around the river banks in the western part to about 450m above mean sea level at Mount Patti Ridge in the northern part. The city is drained by two major rivers of Niger and Benue which form a confluence around the north-eastern corner of the city. Other tributaries include River Meme and River Oinyi. The climate is characterized by wet and dry seasons. Rainfall that characterizes the wet season begins from April and ends in November. The dry season on the other hand begins from November to April (Odekunle, 2006). Temperature in this region is hot all year round.

The study area is overlain by both the Precambrian Basement Complex rocks and Campanian-Maastrichian sedimentary rock successions of the Southern Bida Basin (Aigbadon et al. 2023). The Basement Complex rocks are dominantly characterized by migmatites, gneisses and granitic rocks intruded by the NE-SW trending pegmatite dykes (Grant et al. 1972; Odigi 2000). From the sedimentary basin, three (3) stratigraphic units are recognized. These include the Upper Cretaceous Lokoja sandstone (comprising basal conglomerates and sandstone interbedded with siltstone and claystone), the Patti formation (consist of fine to medium-grained grey and white sandstones, clays and carbonaceous silts, shales, oolitic ironstone and thin impure coal seams) and the Agbaja ironstones (consist of sandstones and claystones interbedded with oolitic, concretionary and massive ironstone beds) (Akande et al. 2005; Obaje 2009; Obaje et al. 2011; Sanni et al. 2016; Ojo and Akande 2020).

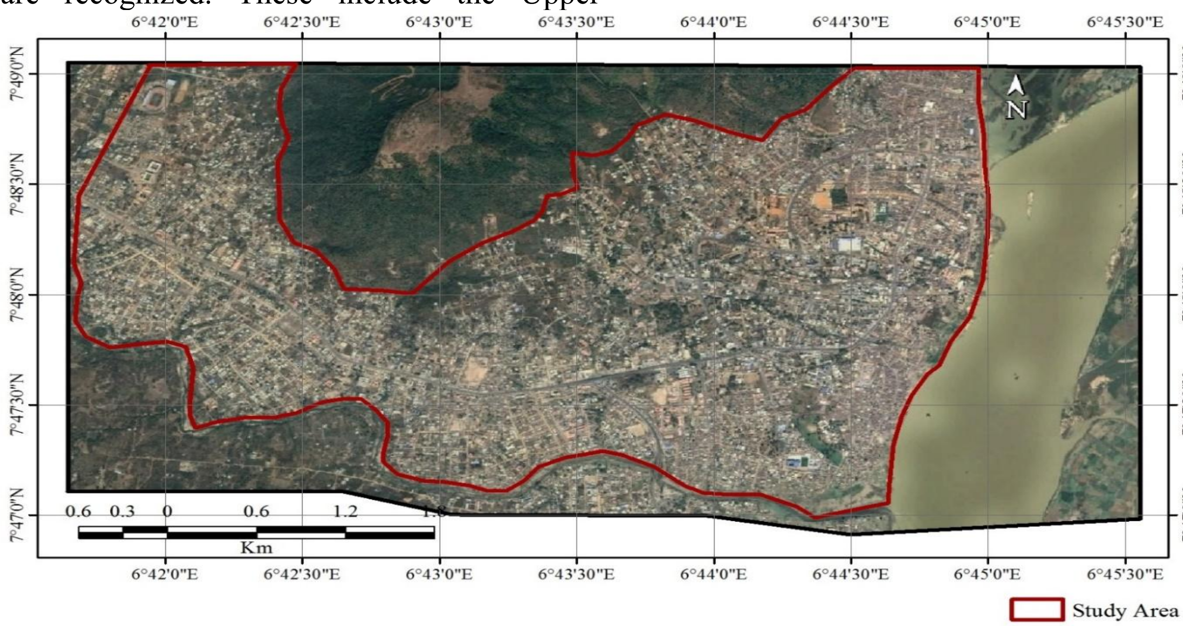

Fig. 1: Google Earth image of the study area

2.0 Materials and Method

This study was executed in generally four (4) broad steps. The first step is the extraction of lineaments and slope from Sentinel-2A and ASTER GDEM image data respectively. These datasets were downloaded from the European Space Agency's Copernicus Programme website and USGS website (www.earthexplorer.usgs.gov) respectively. The Sentinel-2A data comprised a level-2A atmospherically corrected surface reflectance (SR) image acquired on 02-01-2024 with tile number 32NKP. The image comes with 13 spectral bands and spatial resolutions ranging from 10 m - 60 m, is radiometrically and geometrically corrected. The ASTER GDEM on the other hand, is a single band image with a spatial resolution of 30m that provides information on the topographic and hydrology (e.g. elevation, slope and streams). From the Sentinel-2A data, lineaments of the study area were extracted using the automatic extraction method in PCI Geomatica computing environment. In between the extraction process, the image data underwent processing (principal component analysis, image directional filtering and line extraction procedures) and post processing (false lineaments removal and lineament intersection). Thereafter, the lineament density map of the study area was generated and classified into 3 classes of low, moderate and high densities. Details of these steps can be found in Ahmed II et al. (2024).

The ASTER GDEM was utilized to generate the slope map of the study area. Slope was derived from the ASTER GDEM using the slope percent function in ArcGIS 10.8. The slope function identifies rate of maximum change in z-values from each cell of the DEM data. After extraction, the study area shapefile was used to clip the extent of the study area after which the result output was also classified into 3 classes viz; low, moderate and high slope areas.

In the second step, terrain stability (landslide susceptibility) assessment was conducted using lineaments density and slope as parameters. The lineament density map was overlain onto the slope classified map. The intersect geoprocessing tool in ArcGIS computing environment was utilized to compute the geometric intersections between the 3 different classes of the parameters. Where the high lineament density areas intersect with high slope areas gives rise to highly unstable terrain and vice versa.

In the third step, the study area was gridded into 23 square grids each covering about 0.8km^2. From each grid, a total of 12 buildings were randomly sampled and the coordinate locations properly recorded. These buildings which are mostly residential buildings were then separated into buildings with noticeable structural defects and those without any defect. The data was then cleaned, digitized and overlaid on a slope stability map of the study area. Further analyses to visualize the relationships between buildings with noticeable defects and proximity to unstable terrain were conducted.

In the final step, lineaments density together with slope percent were used as parameters to identify areas with good groundwater potential for the study area. The intersect function in geoprocessing tools was utilized to compute areas with high lineament density and low slope gradient as high groundwater potential areas, whereas areas with low lineament density and high slope gradient were recognized as low potential areas for groundwater. Furthermore, borehole completion data were obtained from the field through pumping test. A total of eleven (11) borehole data were used. The yield (l/s) of the boreholes were classified into high, moderate and low yields for the purpose of validating the groundwater potential map.

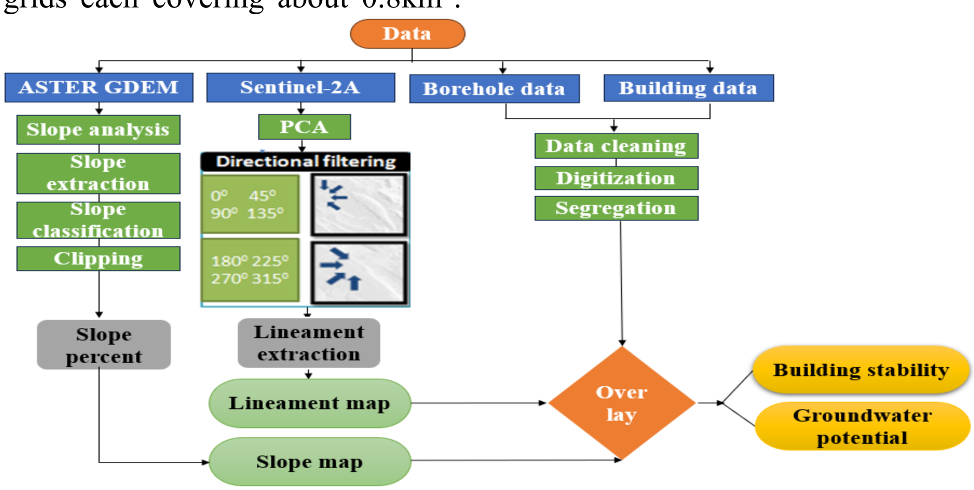

Fig. 2: The methodology flow chart

3.0 Results and discussion

3.1 Lineament extraction

The line module automatic extraction algorithm resulted in the identification and subsequent extraction of few lineaments in the study area. Statistics indicated that a total of 13 lineaments were extracted. The lengths of the lineaments vary from 0.105 km to 3.69 km long with a mean length of 1.14 km making a total length of 14.79 km (table 1). The lineaments which are mostly striking in the NE-SW direction (Fig. 3) are longer and denser towards the southern and northeastern plains while they are shorter and less dense towards the hilly north.

3.2 Slope

Slope extraction analysis revealed that slope in the study area range between 0 – 33%. The slope map which was classified into 3 classes (fig. 4) indicated the prevalence of escarpments surrounding the northern fringes of the study area and a few other high slopy areas around the central part. The high slope areas are related to the Mount Patti ridge that stretches in a NE-SW direction with a maximum elevation of about 458m above mean sea level. This notable feature influences the local topography and drainage patterns of the study area. Further from the northern fringes, the slope generally reduces to gentle rise and fall except in some few isolated cases.

Table 1: Length and strike directions of extracted lineaments

S/N	Length (m)	% of total length	Strike direction
1	573.88	3.88	NE-SW
2	3691.75	24.96	NE-SW
3	1791.22	12.11	NE-SW
4	678.65	4.59	NE-SW
5	1556.41	10.52	NE-SW
6	520.53	3.52	E-W
7	987.13	6.67	NE-SW
8	978.78	6.62	NNE-SSW
9	2119.51	14.33	E-W
10	257.56	1.74	NE-SW
11	523.97	3.54	NE-SW
12	105.79	0.72	NE-SW
13	1006.53	6.80	NE-SW

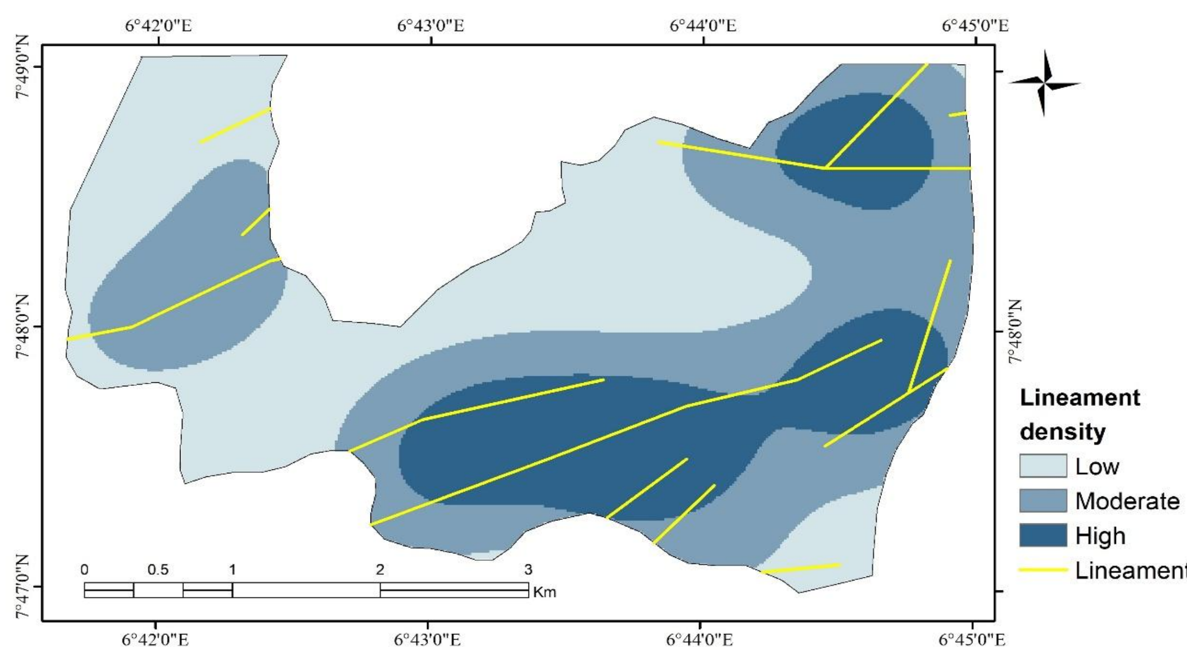

Fig. 3: Lineament map of the study area

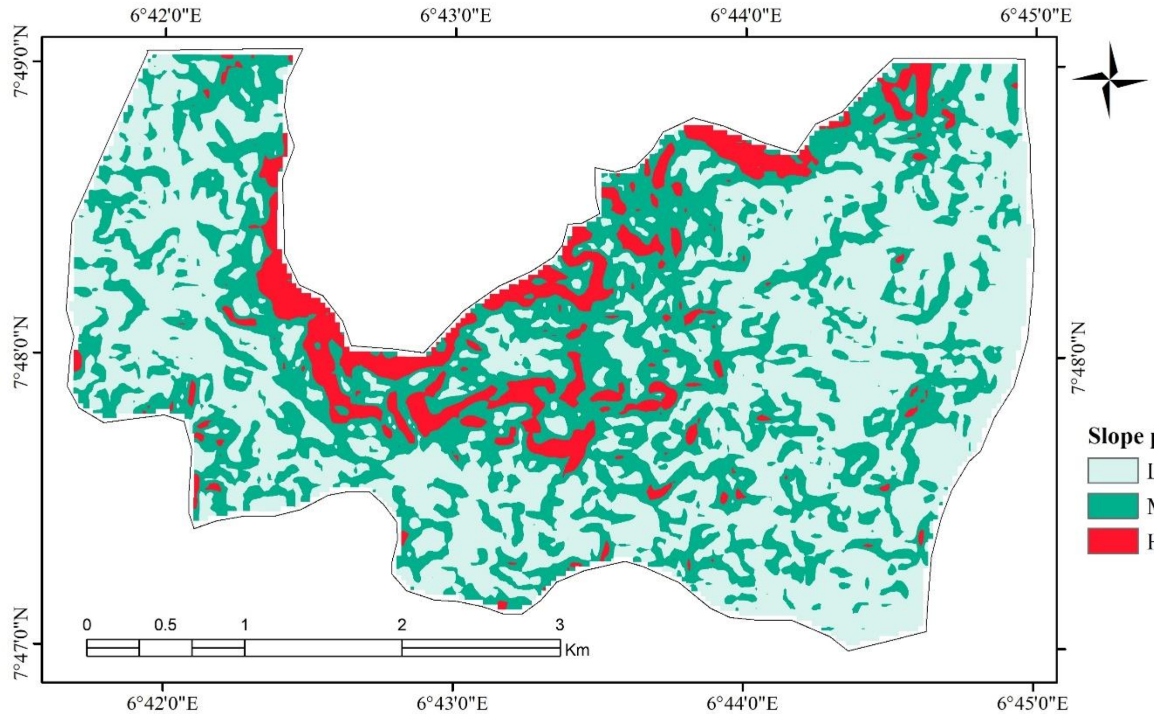

Fig. 4: Slope map of the study area

3.2.1 Terrain stability assessment

Relatively flat and safe land is now limited in the study area. Lokoja metropolis is sandwiched between hills and rivers that usually result in annual inundation. This challenge has compelled development to advance onto hilly areas which pose risk of structural instability that can result in slope failures. GIS analyses using the intersect function between the 3 different classes of lineament density and slope percent, aided in identifying the stable and most unstable areas in the study area (Fig. 5).

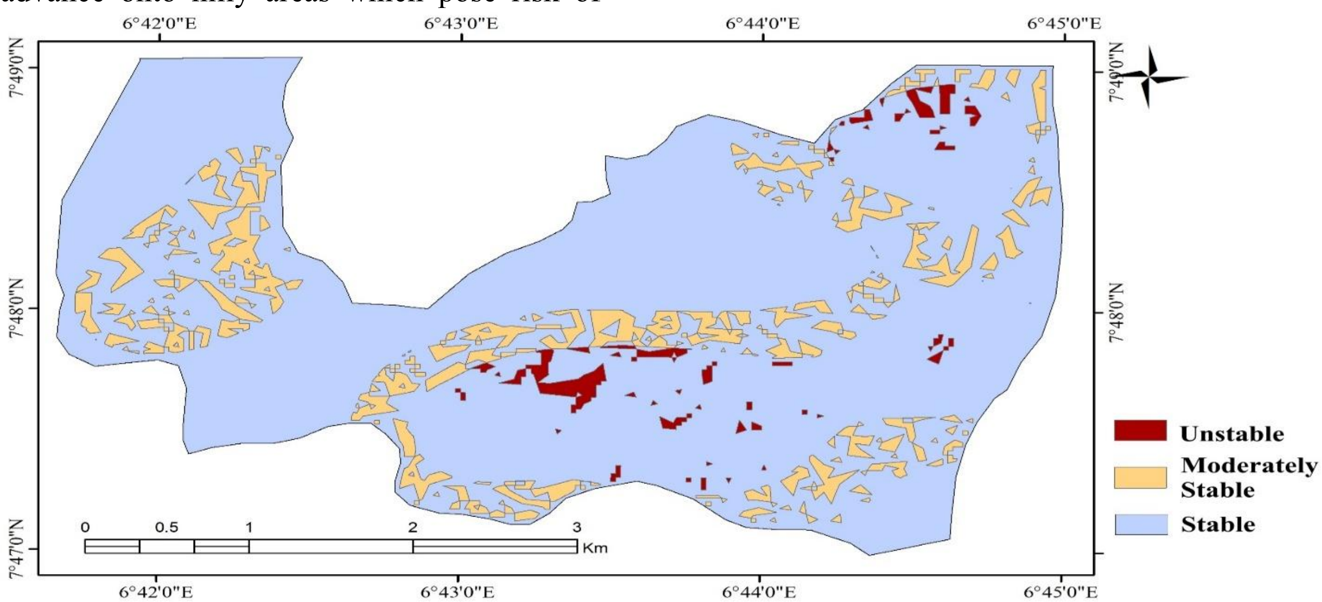

Fig. 5: Terrain stability map

3.3 Buildings structural integrity

Survey of buildings in the study area recorded a total number of 240 buildings out of which 175, representing about 73% were found to have one or more structural problems. These structural defects include cracks on the building foundations, cracks between foundation to window level, cracks from window level to roof level, pillar cracks and cracks from foundation to roof level (fig. 6). On the other hand, 65 buildings (27%) were found not to have any of these structural defects. Spatial analysis of the building locations revealed that 7 (4.0%) buildings with defects and 3 (4.6%) buildings without any defects are located on the most unstable areas. Within the moderately stable areas, 47 (26.9%) defective and 17 (26.2%) non defective buildings are situated. The analysis further revealed that most buildings in the study area are situated within the relatively flat and stable areas with 121 (69.1%) and 45 (69.2%) buildings with and without defects respectively (Fig. 7).

Fig. 6: Structural defects on some buildings in the study area

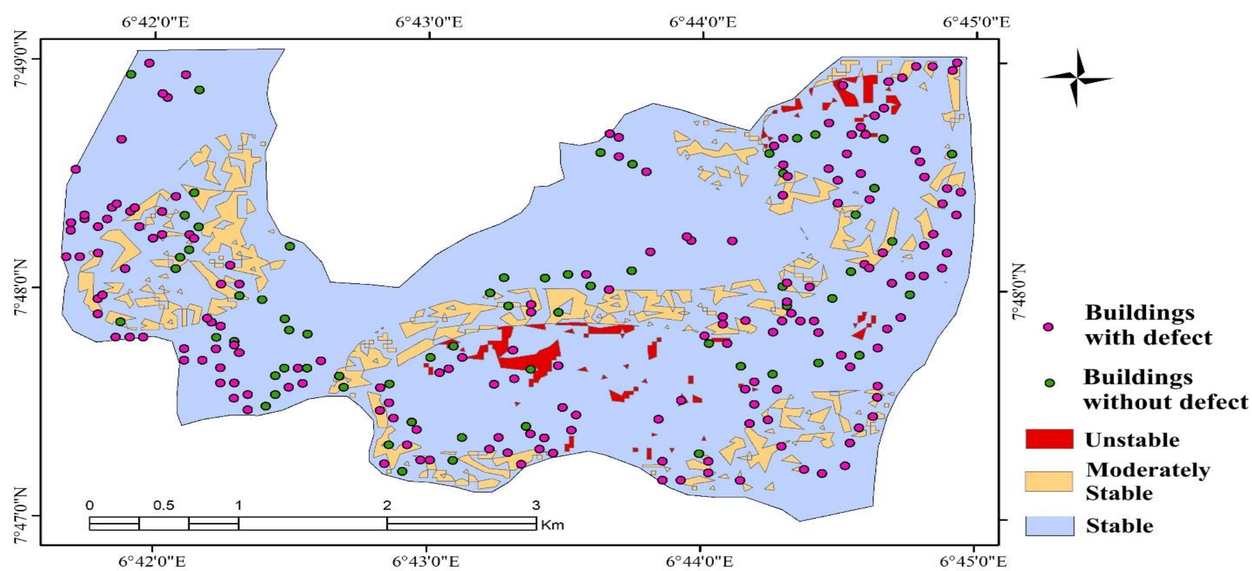

Fig. 7: Superimposition of buildings on slope stability map

3.4 Groundwater potential distribution

The groundwater potential distribution map indicated the spatial variability of groundwater within the study area. The potential map which is produced from the geometric intersection of lineament density and slope gradient maps and zoned into three (3) classes revealed high potential around the southern to eastern part as well as around the northeastern part of the study area. This potential class which covers about 4.20 km^2 (28.6%), represents the relatively flat areas with high lineament density. The moderate potential class covering an aerial extent of about 4.26 km^2 (29.0%), is mostly restricted to the eastern half of the study area. The low potential class corresponds mostly with the northern hilly fringes as well as the western part of the study area. This potential class covers 9.24 km^2 (42.4%) and represents areas with high elevation, steep slopes and low lineament density.

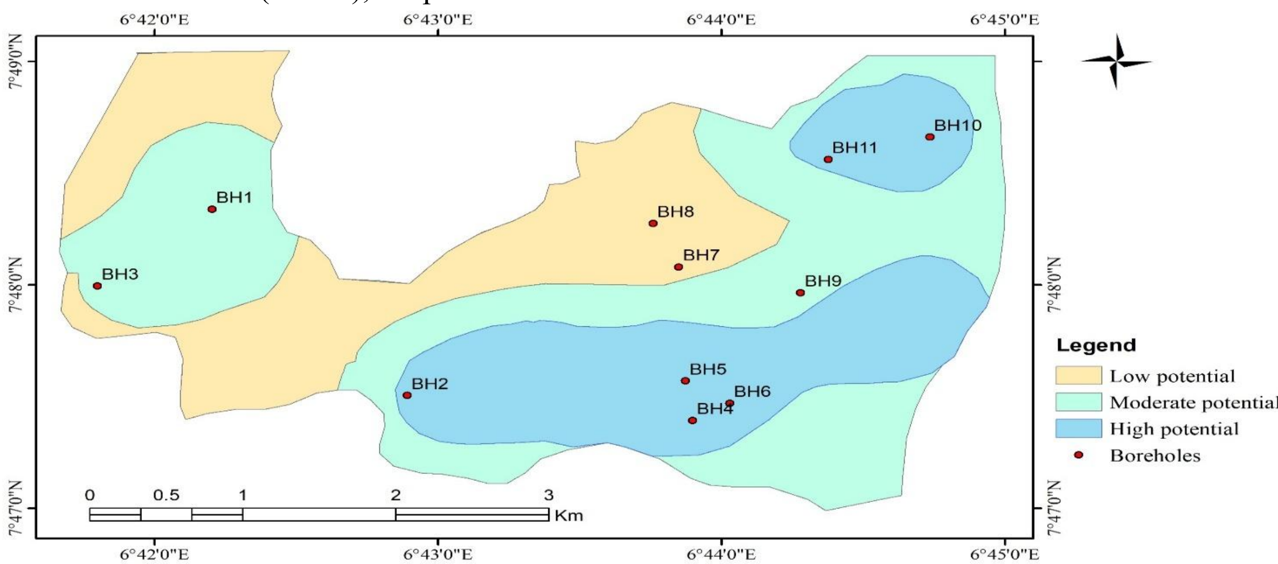

Fig. 8: Groundwater potential map of the study area

3.5 Validation of groundwater potential map

Yield data obtained through pumping test of 11 motorized boreholes (table 2) from different parts of the study area were used to validate the groundwater potential map. The data which is categorized into low yield (<0.5 l/s), moderate yield (0.5 – 1 l/s) and high yield (>1 l/s), were superimposed to the groundwater potential map. The validation result indicated that 50% of low yield boreholes were correctly classified onto the low yield zone. Similarly, 50% of moderately yielding boreholes were correctly classified onto the moderate yield zone. However, the high yielding boreholes were all correctly classified onto the high yield zones. Therefore, the total validation accuracy of the groundwater potential map is 64%.

Table 2: Borehole yield data

ID	Latitude	Longitude	Yield (l/s)
BH1	7.805639	6.703389	0.94
BH2	7.79175	6.714861	0.64
BH3	7.799917	6.696639	0.82
BH4	7.789889	6.731639	1.34
BH5	7.792833	6.731222	1.12
BH6	7.791167	6.733833	1.02
BH7	7.80133	6.730806	0.88
BH8	7.804583	6.729306	0.48
BH9	7.799417	6.737972	0.57
BH10	7.811028	6.745583	0.38
BH11	7.809361	6.739611	0.59

Table 3: Validation of Groundwater Potential Map

	Low yield	Moderate yield	High yield
Low yield	1	0	1
Moderate	1	3	2
High yield	0	0	3

5.0

4.0 Conclusion

This study demonstrated the effectiveness of Sentinel-2A imagery and ASTER GDEM in extracting lineaments and evaluating their implications for slope stability, building structural integrity, and groundwater potential in Lokoja, Nigeria. Thirteen predominantly NE–SW lineaments were identified, with higher densities in the southern and northeastern plains. Steep escarpments along the northern margins, associated with Mount Patti ridge, contrast with relatively gentle terrain in central, southern, and western areas. Integrating lineament density and slope data enabled terrain stability classification, revealing that although some high-slope zones exist, low lineament density suggests moderate stability. The most unstable areas (≈0.25 km²) occur where steep slopes coincide with dense lineaments, particularly in central and northeastern parts. Among 240 buildings surveyed, 73% showed structural defects, though most structures—defective or not—lie on stable terrain, indicating additional contributing factors such as construction quality and soil conditions. Groundwater potential mapping revealed high-potential zones mainly in southern, eastern, and northeastern areas, where flat terrain overlaps high lineament density. Validation with borehole data yielded 64% accuracy, highlighting the need for supplementary hydrogeological information to improve reliability. Overall, the study underscores the value of multisource remote sensing and GIS-based spatial analysis for understanding terrain stability, guiding urban development, and planning groundwater resources in rapidly growing cities like Lokoja.

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Declaration

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data public

Ethical Considerations

Not applicable

Competing interest

The authors report no conflict or competing interest

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Authors' Contributions

J. B. Ahmed II conceptualized the study, designed the methodology, and supervised all research stages. He performed data acquisition, remote sensing analysis, lineament extraction, terrain stability assessment, and groundwater potential mapping. He interpreted results, coordinated validation using borehole data, and led manuscript preparation, including drafting the abstract, discussion, and conclusion, ensuring scientific quality and coherence across all sections of the paper.