

Application of Remote Sensing and Geographic Information System in Groundwater Potential Assessment of Palladan, Zaria, Northwestern Nigeria

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APPLICATION OF REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEM IN GROUNDWATER POTENTIAL ASSESSMENT OF PALLADAN, ZARIA, NORTHWESTERN NIGERIA

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Abstract

Groundwater is an important source of water for domestic, agricultural, and industrial activities, particularly in basement complex terrains where its occurrence is controlled by surface and subsurface geological conditions. This study assessed the groundwater potential of Palladan, Zaria, Northwestern Nigeria, using remote sensing and Geographic Information System (GIS) techniques. Landsat 9 Operational Land Imager (OLI) satellite imagery and Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data were acquired and processed to generate thematic layers, including land use/land cover, lineament density, drainage density, and slope. The Landsat 9 imagery was processed using ENVI software, while ArcGIS was employed for spatial analysis, thematic mapping, and integration of the groundwater-influencing factors. Land use/land cover classification was performed using the Maximum Likelihood Classification technique, whereas lineaments were extracted from enhanced satellite imagery using directional filtering and PCI Geomatica. The thematic layers were reclassified according to their relative suitability for groundwater occurrence and integrated using the Analytical Hierarchy Process (AHP) and weighted overlay techniques to produce a Groundwater Potential Zonation (GWPZ) map. The results revealed that built-up areas constituted approximately 50% of the study area, bare land 33%, vegetation 15%, and water bodies 2%. The AHP analysis assigned the highest weight to slope (0.5016), followed by drainage density (0.2630), land use/land cover (0.1591), and lineament density (0.0768), with a consistency ratio of 0.051. The resulting groundwater potential assessment identified areas of varying groundwater suitability, with approximately 60% of the study area classified within good to excellent groundwater potential zones. These zones were predominantly associated with gentle slopes, high lineament density, low drainage density, and favourable land cover conditions.

Keywords: Groundwater potential assessment; Remote sensing; Geographic Information System (GIS); Landsat 9 OLI; SRTM DEM; Land use/land cover; Lineament density; Drainage density; Slope; Analytical Hierarchy Process (AHP); Groundwater Potential Zonation; Palladan; Zaria.

1. INTRODUCTION

Groundwater is an important natural resource that supports domestic, agricultural and other human activities. Its occurrence and distribution are controlled by several environmental and geological factors, particularly in crystalline basement terrains. In such terrains, groundwater occurrence is generally associated with zones of weathering, fracturing and favourable surface conditions that enhance infiltration and recharge. Consequently, identifying areas with favourable groundwater conditions requires the integration of different spatial datasets.

Palladan is a densely populated area within the Zaria basement complex where groundwater is an important source of water supply. Previous investigations reported concerns associated with unsuccessful and abandoned boreholes in the area, emphasizing the need for improved groundwater exploration and planning. The heterogeneous nature of basement complex terrains makes groundwater occurrence difficult to determine from surface observations alone. Remote sensing provides a non-contact means of obtaining spatial information about surface conditions and geological structures, while GIS provides a suitable environment for integrating and analysing the resulting thematic information.

Remote sensing and GIS techniques have been applied successfully in groundwater potential investigations by integrating parameters such as slope, drainage density, lineament density and land use/land cover. Mukhtar et al. (2021), for example, demonstrated the application of satellite data and GIS for groundwater potential analysis in Fakai, Northwestern Nigeria. Waikar et al. (2014) similarly integrated thematic layers using remote sensing and GIS to delineate groundwater potential zones. Sener et al. (2005) also demonstrated the usefulness of integrating remote sensing and GIS techniques in groundwater investigations.

This study therefore focuses on the application of remote sensing and GIS to assess groundwater potential in Palladan, Zaria. Four major groundwater-influencing factors—land use/land cover, lineament density, drainage density and slope were derived and integrated using the Analytical Hierarchy Process (AHP) to produce a Groundwater Potential Zonation map.

2. LOCATION AND GEOLOGY OF THE RESEARCH AREA

The study area is located in Palladan, Zaria, within the Zaria basement complex of Northern Nigeria. It is situated adjacent to the Nigerian College of Aviation Technology and near the Nigerian Institute of Transport Technology. The broader Zaria basement complex lies approximately between latitudes $11^{\circ}03'N$ and $11^{\circ}11'N$ and longitudes $07^{\circ}37'E$ and $07^{\circ}42'E$, with an average elevation of about 670 m above sea level. The specific study area extends from approximately latitude $11^{\circ}08'37''N$ to $11^{\circ}08'56''N$ and longitude $7^{\circ}41'13''E$ to $7^{\circ}41'35''E$.

The area forms part of the Zaria-Kano plains and is characterized by crystalline basement rocks. The regional geology comprises basement complex rocks including granitic and gneissic units, with surficial materials including lateritic and clayey soils. The basement complex setting is important to groundwater occurrence because weathering and structural features can influence infiltration, groundwater storage and movement.

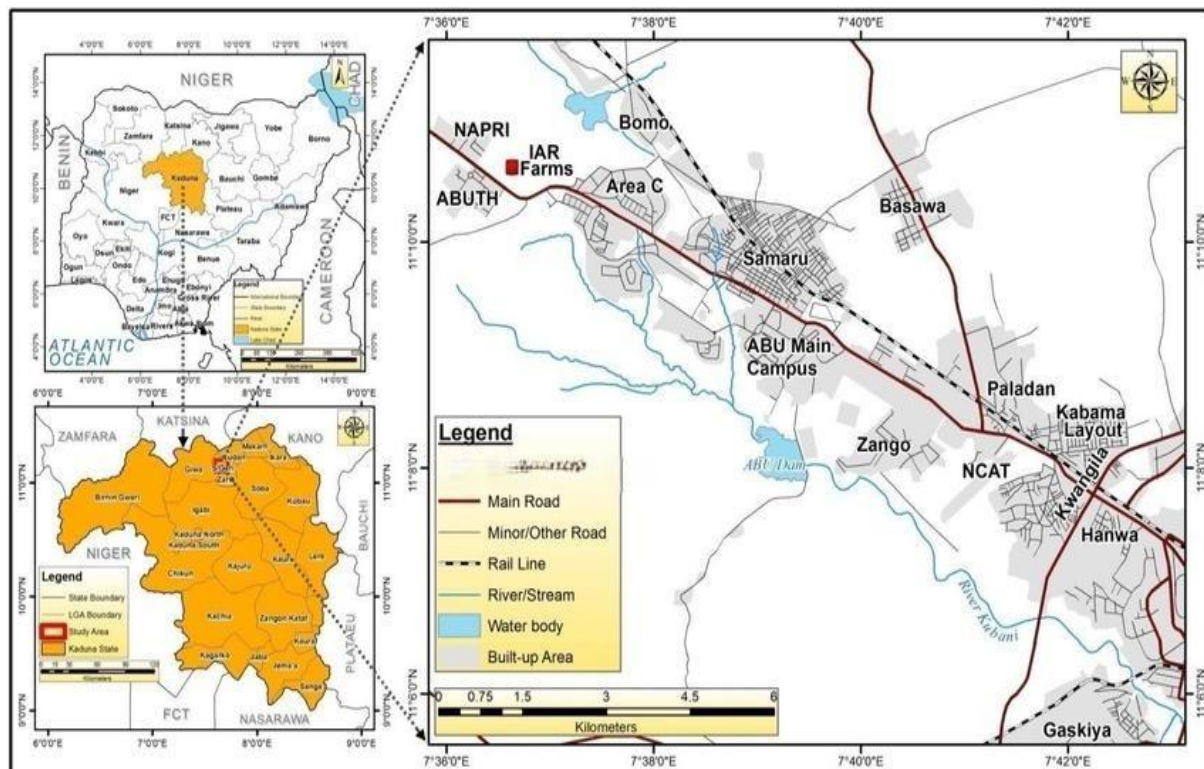


Figure 2.1: Location Map of the Study Area (Modified from NGSA, 2016)

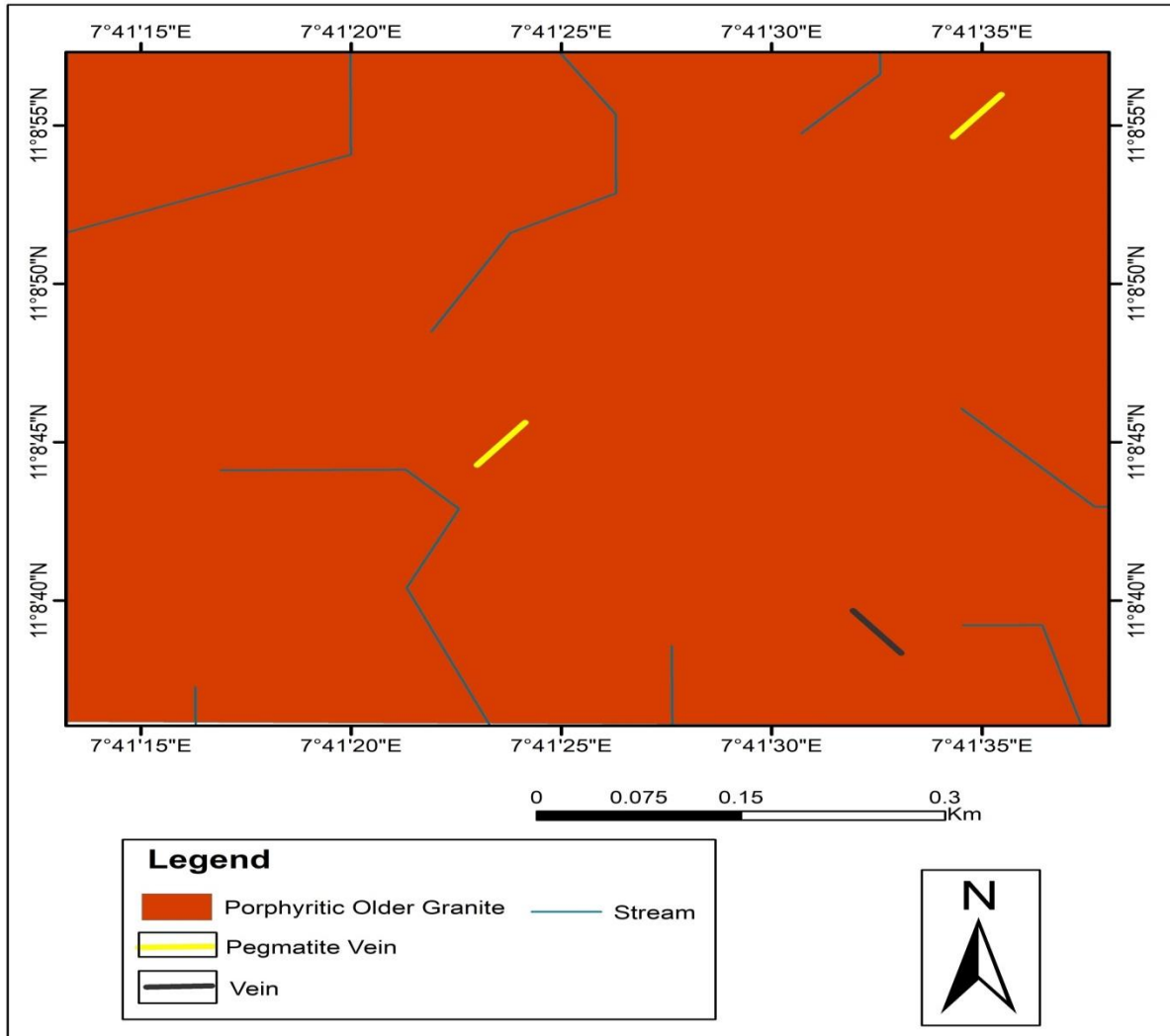


Figure 2.2: Geological Map of the Study Area (Modified from NGSA, 2016)

3. MATERIALS AND METHODS

3.1 Materials

The remote sensing and GIS investigation utilized Landsat 9 OLI satellite imagery, SRTM Digital Elevation Model data, ENVI 5.3, PCI Geomatica 2018 and ArcGIS software. The satellite image was acquired from the US Geological Survey Earth Explorer platform.

3.2 Data Acquisition and Pre-processing

A Landsat 9 OLI satellite image covering scene Path 184 and Row 55 was acquired between 29 March and 5 April 2024. The image was downloaded from the US Geological Survey Earth Explorer portal. The imagery was projected to the Universal Transverse Mercator coordinate system using WGS84 Zone 32N. The thematic layers were resampled to a 30 m spatial resolution using the nearest-neighbour method.

Image enhancement was carried out using ENVI 5.3. A false-colour composite was produced using bands 6, 5 and 4, representing the short-wave infrared, near-infrared and red portions of the electromagnetic spectrum, respectively.

3.3 Generation of Thematic Layers

Four thematic layers relevant to groundwater potential were generated: land use/land cover, lineament density, drainage density and slope.

3.3.1 Land Use/Land Cover

Land use/land cover classification was performed using Anderson's Level I classification system. Four classes were identified: built-up areas, bare land, vegetation and water bodies. The Landsat composite was subjected to supervised classification using the Maximum Likelihood Classification technique.

3.3.2 Lineament Density

Lineaments were extracted from the enhanced Landsat imagery. A directional convolution filter with a 5×5 kernel was applied in ENVI. Four principal directions were considered: north-south (180°), northwest-southeast (135°), northeast-southwest (225°) and east-west (270°).

The filtered images were subsequently processed in PCI Geomatica 2018 using the Line module. Edge detection, thresholding and curve extraction were employed to identify linear features. The extracted lineaments were used to generate the lineament-density layer.

3.3.3 Drainage Density

Drainage density was used as an indicator of surface runoff and groundwater recharge conditions. It represents the ratio of the total length of drainage channels to the area over which they occur. The drainage network was analysed spatially and classified into five categories: very high, high, medium, low and very low drainage density.

High drainage density was considered indicative of greater surface runoff and relatively lowers infiltration, whereas low drainage density was associated with reduced runoff and more favourable infiltration conditions.

3.3.4 Slope

The SRTM DEM was used to generate a slope map in ArcGIS. The slope was calculated in degrees using the Slope tool. The resulting slope map was classified into five categories: 0–1° (very gentle), 1–2° (gentle), 2–3° (moderate), 3–5° (steep) and greater than 5° (very steep).

3.4 Analytical Hierarchy Process and Weighted Overlay

The Analytical Hierarchy Process (AHP) was employed to assign weights to the thematic layers used in this study. AHP is a reliable and structured decision-making tool that effectively integrates both qualitative and quantitative components in multi-criteria analysis. It simplifies the evaluation process through pairwise comparisons of the selected criteria.

In this study, four thematic layers were used. They were evaluated using pairwise comparison within the AHP framework. The resulting decision matrix (D), as shown in Equation 3.1, consists of elements x_{ij} , which represent the relative importance or preference of the i -th criterion over the j -th criterion (or vice versa), providing a basis for calculating their relative weights.

$$D_{ij} = x_{ij} \quad 3.1$$

In aggregating the responses, the average pair wise comparison matrix (D) was determined using Equation 3.2 and the results are shown in table 3.2

$$\bar{D}_{ij} = \bar{x}_{ij} \quad 3.2$$

Table 3.1: Pairwise comparison matrix

Layer	S	Dd	LULC	Ld
S	1	3	3	5
Dd	0.33	1	3	3
LULC	0.33	0.33	1	1
Ld	0.2	0.33	1	1

Using Eq. 3.3, the normalized comparison matrix (R) was calculated. Table 3.2 presents the outcomes. The priority weights for the various levels are represented in Table 3.3 as normalized comparison weights.

$$D_{ij} = \frac{x_{ij}}{\sum_{i=1}^n x_{ij}} \quad 3.3$$

Table 3.2: Normalized comparison matrix (R)

Layer	S	Dd	LULC	Ld
S	0.5351	0.6429	0.4091	0.4167
Dd	0.1786	0.2143	0.4091	0.2500
LULC	0.1786	0.0714	0.1364	0.2500
Ld	0.1071	0.0714	0.0455	0.0833

Consistency Index (CI) = 0.045; Random Index (RI) = 0.90; Consistency Ratio (CR) = 0.051

Table 3.3: Priority weight for thematic layers

Thematic Layer	Priority Weight
Slope	0.5016
Drainage density	0.2630
LULC	0.1591
Lineament density	0.0768

The consistency index (CI) and the consistency ratio (CR) were calculated using equation 3.4 and 3.5 respectively.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad 3.4$$

Where λ_{max} represents the principal eigenvalue of the matrix D having an order of n which is the number of criteria considered.

$$CR = \frac{CI}{RI} \quad 3.5$$

In the ArcGIS, the weighted overlay tool was used, with the weights determined for the layers and the ranks of the subclasses. The outcome of the weighted overlay algorithm was used to produce three classes: high, moderate, and low groundwater potential. The groundwater potential index (GWPI) in Equation 3.6 was used to integrate the final four (4) chosen thematic layers. The total normalized weights for the strata were integrated to derive the GWPI. The total groundwater potential map was created when the raster calculator tool in the ArcGIS 10.4 was used to execute Equation 3.6. The information from the aforementioned layers was combined in the ArcGIS to create the groundwater potential zones (GWPZ) map.

$$GWPI = Dd_w Dd_{w1} + Ld_w Ld_{w1} + LULC_w LULC_{w1} + S_w S_{w1} \quad 3.6$$

where, Dd is drainage density, Ld is lineament density, LULC is land use/land cover, S is slope, w is normalized weight of the thematic layer and w_i is the normalized weight of sub-layer classes.

Table 3.4 presents the Saaty Fundamental Scale developed by Saaty (1980), which is used in the Analytic Hierarchy Process (AHP) to assign relative importance to decision criteria. The scale ranges from 1 to 9, representing levels from equal to extreme importance. It provides a systematic basis for comparing criteria and determining their relative weights in the groundwater potential assessment.

Table 3.4 : Saaty Fundamental Scale (1980)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
2	Weak or slight	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favour one element over another.
4	Moderate plus	Intermediate value between moderate and strong importance.
5	Strong importance	Experience and judgment strongly favour one element over another.
6	Strong plus	Intermediate value between strong and very strong importance.
7	Very strong importance	One element is strongly favoured, and its dominance is demonstrated in practice.
8	Very, very strong	Intermediate value between very strong and extreme importance.
9	Extreme importance	The evidence favouring one element over another is of the highest possible order of affirmation.

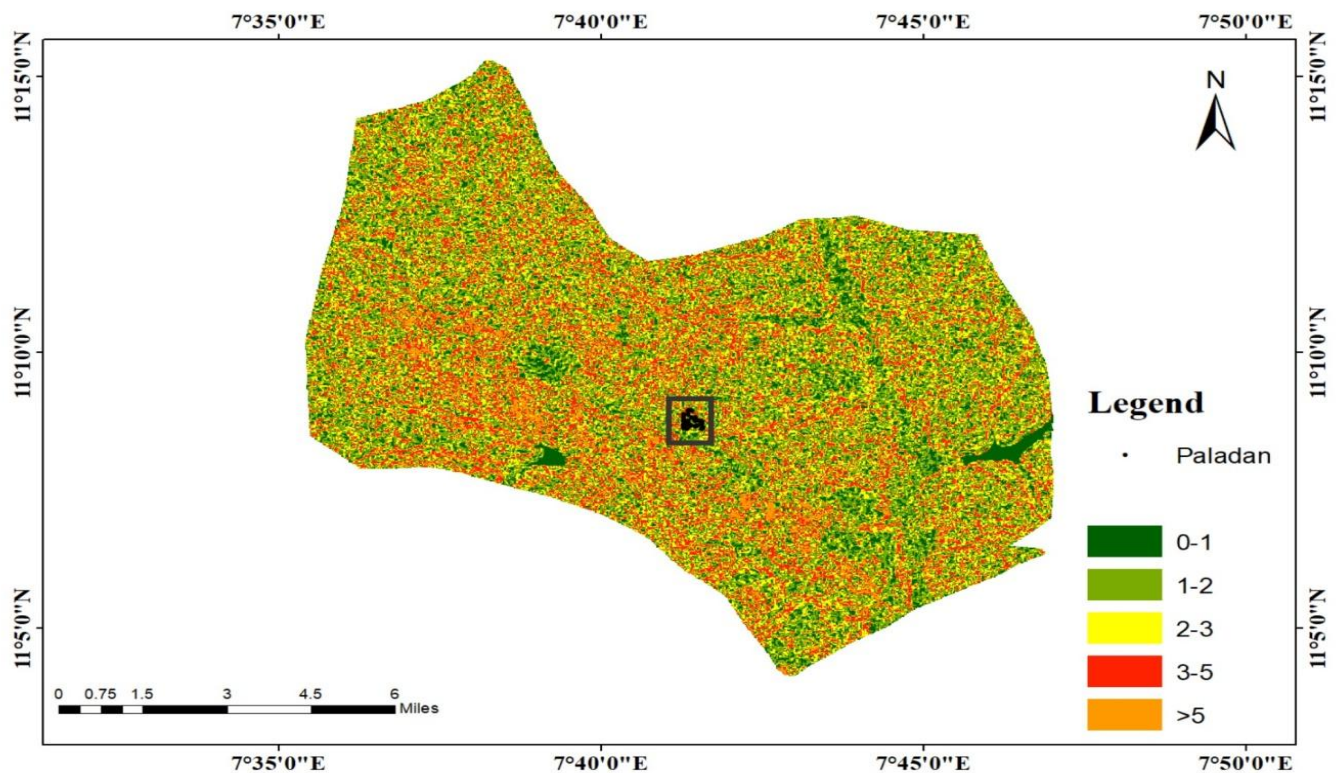
4. RESULTS

The results of the remote sensing and GIS analysis are presented based on the thematic layers generated from Landsat 9 OLI imagery and SRTM DEM data. The analysis focused on four major factors influencing groundwater potential in the study area: land use/land cover, lineament density, drainage density and slope. These thematic layers were independently analysed to determine their spatial distribution and groundwater significance before being integrated using the Analytical Hierarchy Process (AHP) and weighted overlay techniques. The resulting

Groundwater Potential Zone (GWPZ) map was used to identify areas with varying degrees of groundwater potential across Palladan.

4.1 Slope

Figure 4.1: The slope map of the research area



The slope plays a critical role in groundwater studies, as it significantly influences runoff, Infiltration rates and groundwater recharge potential. The slope map (Figure 4.1) provides a detailed understanding of the terrain's gradient across the research area. The slope map revealed that a substantial portion of the study area is characterized by gentle to moderate terrain, with slopes ranging from 0° to 3°. These areas occur extensively within the central, northern and southeastern portions of the study area.

The 0–1° slope class represents very gentle terrain and provides relatively favourable conditions for infiltration because surface water can remain on the ground for longer periods. In contrast, areas with slopes of 3–5° and greater than 5° occur mainly in the southwestern portion and in

scattered areas near the northern boundaries. These steeper areas favour more rapid surface runoff and comparatively reduced infiltration.

4.2 Land Use/Land Cover

The Land Use and Land Cover (LULC) distribution within the study area is shown in (Figure 4.1). The LULC classification identified four major classes within the study area: built-up area, bare land, vegetation and water body. Built-up areas constituted approximately 50% of the study area and were concentrated mainly in the central, eastern and parts of the northern portions. The extensive built-up coverage represents largely impervious surfaces that can reduce infiltration and increase surface runoff.

Bare land covered approximately 33% of the area and occurred mainly in the northern and central portions. Vegetation accounted for approximately 15% and was concentrated mainly in the southern and southeastern portions. Water bodies constituted approximately 2% and were largely associated with vegetated areas.

The distribution indicates that vegetated areas and water bodies provide relatively favourable surface conditions for infiltration and recharge, while extensive built-up areas may limit infiltration.

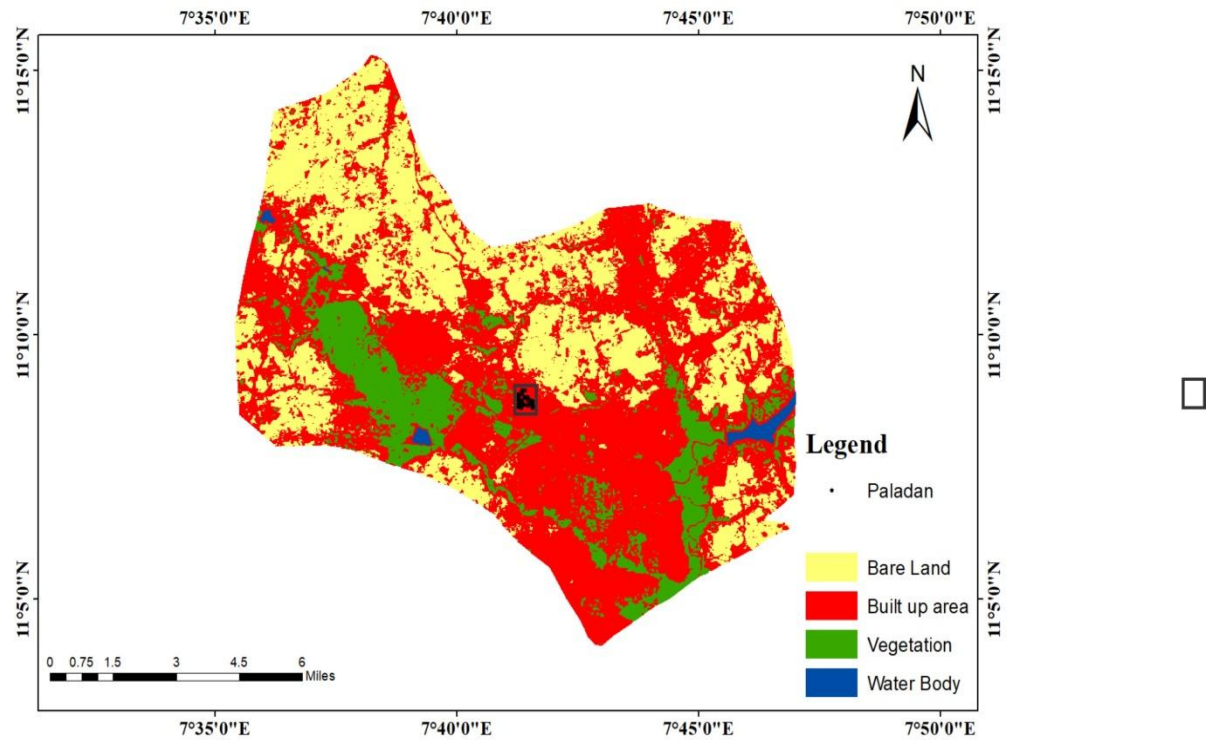


Figure 4.2: Land Use/Land Cover Map of the Study Area

4.3 Drainage Density

The drainage density map (Figure 4.3), shows the spatial distribution of drainage density across the study area. Drainage density refers to the total length of streams and rivers in a given area divided by the total area, and are a crucial parameter for assessing groundwater potential. The drainage-density map classified the study area into very high, high, medium, low and very low drainage-density zones. Very high and high drainage-density zones occur mainly in the southern and central portions, with drainage patterns showing predominantly north-south and northwest-southeast orientations.

These areas may experience relatively greater surface runoff and reduced infiltration. However, the presence of structural features or valleys may locally enhance recharge through secondary pathways.

Medium, low and very low drainage-density zones dominate the northeastern and peripheral parts of the study area. These zones are associated with relatively lower surface runoff and potentially greater infiltration, making them more favourable for groundwater recharge.

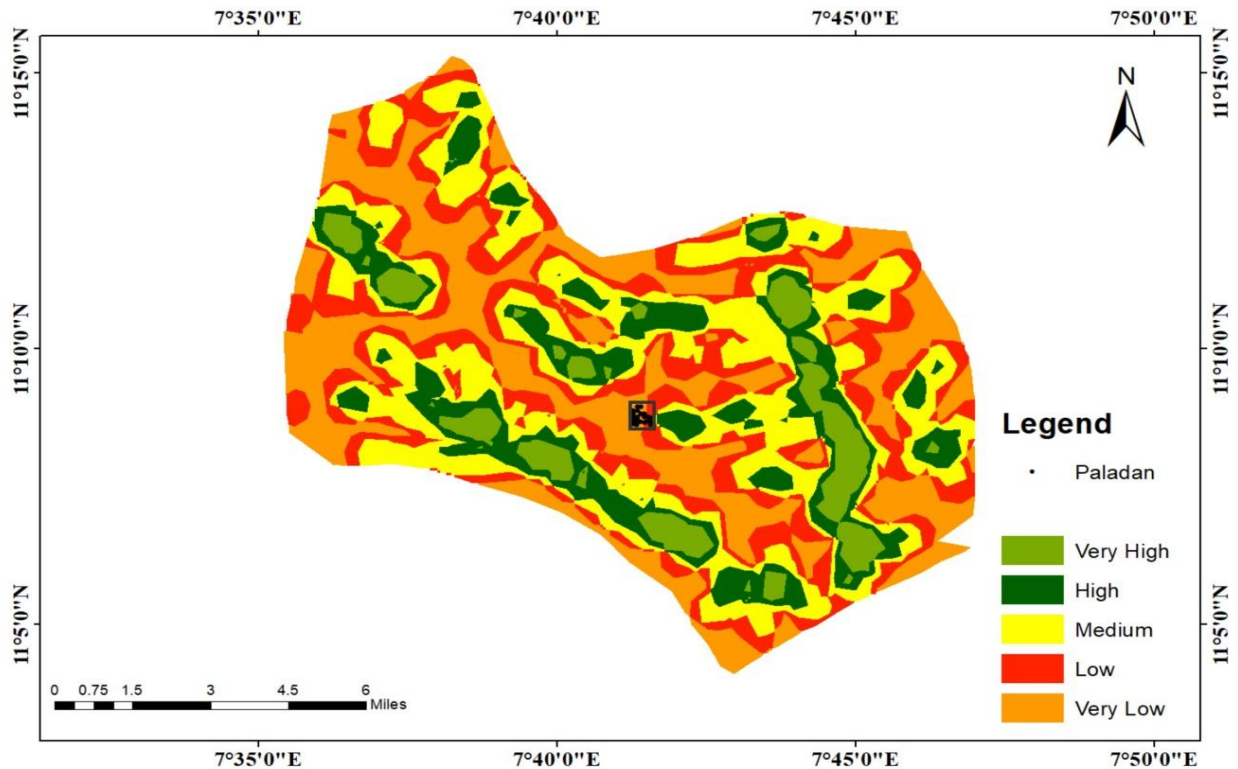


Figure 4.3: Drainage Density Map of the Study Area

4.4 Lineament Density

The lineament density map of the area reveals significant spatial variation in the distribution (Figure 4.4) and concentration of linear geological features, which are critical indicators of groundwater occurrence. Lineaments such as faults, fractures, and joints enhance secondary porosity and permeability by facilitating subsurface water infiltration and movement. Five lineament-density classes were identified: very high, high, medium, low and very low.

Very high and high lineament-density zones occur predominantly in the central, northeastern and southwestern portions of the study area. These areas contain relatively dense networks of linear

features and may provide pathways for groundwater movement through enhanced secondary porosity and permeability.

Low and very low lineament-density zones occur mainly along peripheral portions of the study area, particularly in the western and southeastern areas. Such areas contain fewer identifiable structural features and may therefore provide fewer structural pathways for groundwater movement.

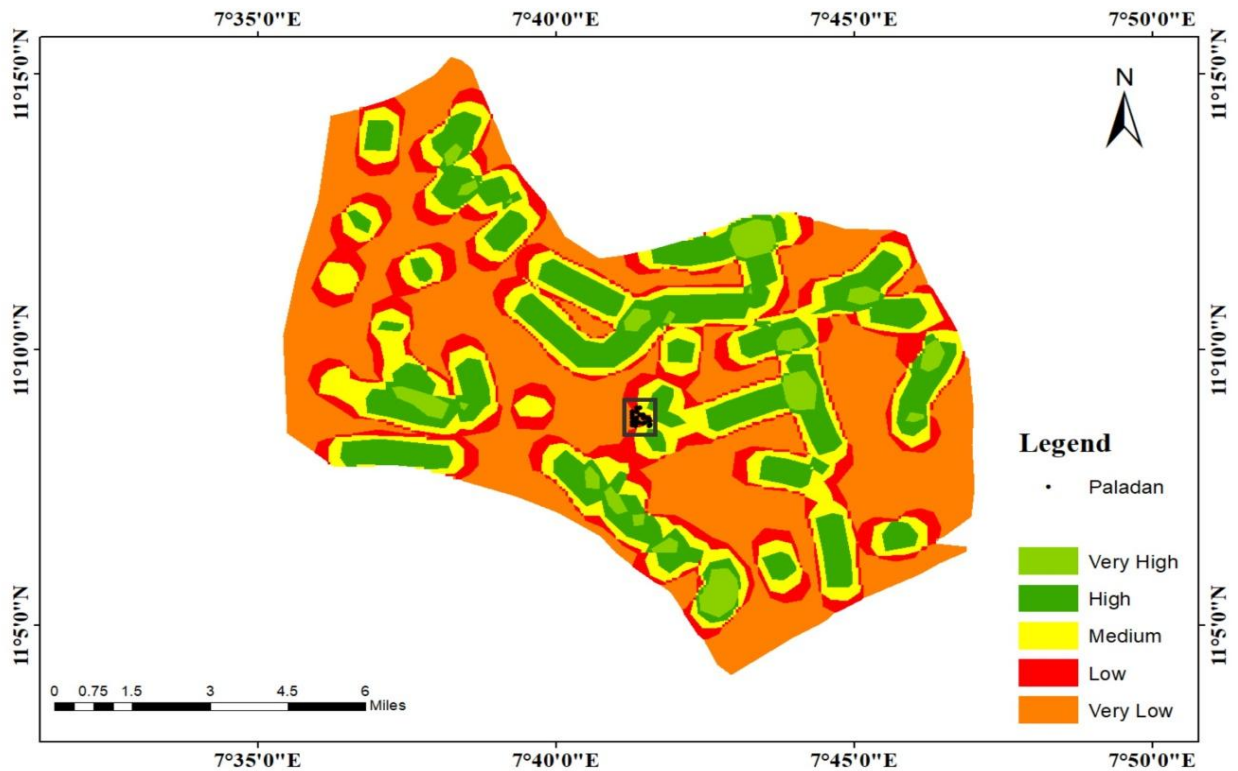


Figure 4.4: Lineament Density Map of the Study Area

4.5 GROUNDWATER POTENTIAL ZONE

The groundwater potential zones map reveals a spatial variation in groundwater availability across the study area. The groundwater potential zoning integrates layers such as lineament density, slope, drainage density, and land use/land cover to classify areas based on their capacity to store and transmits groundwater. Figure 4.5 displays the spatial distribution of groundwater

potential zones in the study area. The Groundwater Potential Zonation map consisting of five classes: poor, fair, moderate, good and excellent.

Approximately 60% of the study area falls within the good to excellent groundwater potential classes. These zones occur mainly in the northern, central and southeastern parts of the area and are associated with favourable combinations of gentle slopes, high lineament density, low drainage density and suitable land-cover conditions.

Moderate groundwater potential zones occur throughout the study area and generally form transition zones between the more favourable and less favourable areas. Fair and poor potential zones occupy smaller portions of the study area and occur mainly in areas characterized by steeper terrain or relatively high drainage density, particularly in the southwestern and scattered northeastern portions.

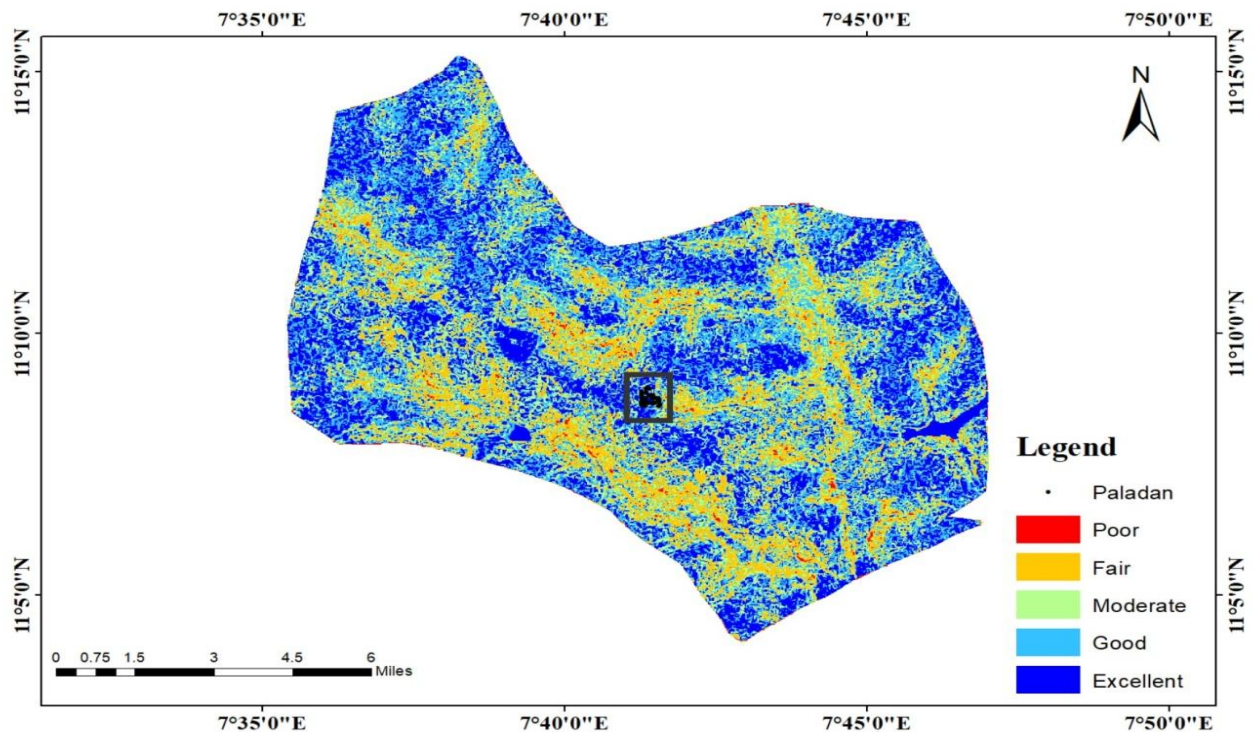


Figure 4.5: Groundwater Potential Zonation Map of the Study Area

5. DISCUSSION

The remote sensing and GIS analysis demonstrates that groundwater potential in Palladan varies spatially according to the combined influence of surface and structural factors. The LULC distribution indicates substantial urban development, with built-up areas accounting for approximately half of the study area. The concentration of impervious surfaces in the central and eastern portions may restrict infiltration, whereas vegetated areas in the southern and southeastern portions provide more favourable conditions for infiltration and soil-moisture retention.

Lineament density provides an indication of the structural control on groundwater movement. The occurrence of high and very high lineament-density zones in parts of the central, northeastern and southwestern areas suggests the presence of relatively dense structural features that may facilitate groundwater movement and storage. In crystalline basement environments, fractures and joints can provide secondary pathways where primary porosity is generally limited.

Drainage density provides complementary information on runoff and infiltration. The occurrence of low and very low drainage-density zones in the northeastern and peripheral parts indicates areas where runoff may be relatively reduced and infiltration conditions more favourable. Conversely, the concentration of high drainage-density zones in the southern and central portions suggests greater surface runoff and potentially reduced recharge.

Slope also exerts an important influence on groundwater recharge. The dominance of gentle slopes between 0° and 3° over much of the central, northern and southeastern portions of the study area provides relatively favourable conditions for infiltration. Steeper terrain, particularly in the southwestern portion, is associated with increased runoff and reduced opportunity for infiltration.

The AHP results further demonstrate the relative contribution assigned to the four thematic factors in the groundwater potential model. Slope received the highest weight of 0.5016, followed by drainage density with 0.2630, LULC with 0.1591 and lineament density with 0.0768. The consistency ratio of 0.051 indicates that the pairwise comparison used for assigning the weights was internally consistent according to the AHP procedure adopted in the study.

The resulting GWPZ map shows that approximately 60% of the study area belongs to the good and excellent potential classes. The spatial coincidence of these zones with gentle slopes, high lineament density and low drainage density indicates that the combined thematic approach provides useful information for identifying areas with relatively favourable groundwater conditions. Similar applications of remote sensing, GIS and multi-criteria analysis have been reported by Sener et al. (2005), Waikar et al. (2014), Mukhtar et al. (2021) and Akinluyi et al. (2021).

6. CONCLUSION

This study applied remote sensing and GIS techniques to assess groundwater potential in Palladan, Zaria, Northwestern Nigeria. Landsat 9 OLI imagery and SRTM DEM data were used to derive four major thematic layers: land use/land cover, lineament density, drainage density and slope.

The LULC classification showed that built-up areas constituted approximately 50% of the study area, followed by bare land at 33%, vegetation at 15% and water bodies at 2%. The slope analysis showed that much of the area has gentle to moderate slopes ranging from 0° to 3° , while the steeper areas are concentrated mainly in the southwest and parts of the northern boundary. High lineament-density zones occur mainly in the central, northeastern and southwestern portions, while low drainage-density zones occur mainly in the northeastern and peripheral areas.

The AHP assigned the highest weight to slope (0.5016), followed by drainage density (0.2630), LULC (0.1591) and lineament density (0.0768), with a consistency ratio of 0.051. The resulting Groundwater Potential Zonation map classified the area into poor, fair, moderate, good and excellent potential zones. Approximately 60% of the study area was classified as good to excellent, particularly within the northern, central and southeastern portions.

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