

Groundwater Potential Zonation Through Integration of Remote Sensing, Geographic Information Systems and AHP Techniques in FCT Abuja

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ABSTRACT

Groundwater is a vital freshwater resource supporting domestic, agricultural, and industrial demands, especially in semi-arid regions with limited surface water. This study maps groundwater potential zones in the Federal Capital Territory (FCT), Abuja, Nigeria, using an integrated approach combining Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP). These methods enable wide spatial coverage and objective analysis where conventional data are scarce. The study uses thematic datasets—slope, drainage density, lineament density, rainfall, topographic wetness index (TWI), land use/land cover (LULC), geology, and soil type—derived from satellite imagery, government sources, and field surveys (2015–2024). Parameters were weighted with AHP, processed in ArcGIS 10.7.1, and overlaid to produce a composite groundwater potential map. Results show steep slopes dominate over 80% of the area, limiting recharge, while only 2.29% favors infiltration. Moderate to low drainage density supports balanced recharge, while higher densities restrict it. Moderate lineament density aids recharge, though high-density zones risk contamination. Most areas have low TWI, with small recharge hotspots. Vegetation dominates land cover, supporting infiltration, while urbanization hinders it. Overall, the model identifies high, moderate, and low potential zones, supporting sustainable groundwater management.

Keywords: AHP; GIS; Groundwater potential; Remote sensing

1. Introduction

Groundwater is an indispensable resource that sustains human, agricultural, and industrial activities worldwide, particularly in arid and semi-arid regions (Abdulrazzaq et al., 2020). It provides drinking water to nearly half of the world's population, accounts for 43% of irrigation needs, and represents 99% of the Earth's liquid freshwater reserves (Moursy et al., 2023). Despite being concealed beneath the surface, groundwater plays a crucial role in the hydrological cycle, supporting ecosystems, and driving socioeconomic development. Yet, its direct observation and quantification remain challenging, necessitating systematic mapping and monitoring strategies (Levy & Xu, 2011).

The occurrence and distribution of groundwater are controlled by multiple interrelated factors, including climate, geology, hydrology, topography, vegetation, and soil characteristics (Haaf et al., 2020). However, the growing pressure on freshwater resources, compounded by population growth, climate variability, and industrial activities, has heightened the urgency for integrated and cost-effective approaches to groundwater assessment and management (Kalhor et al., 2019).

Remote sensing (RS) and geographic information systems (GIS) have emerged as indispensable tools for groundwater exploration, offering non-invasive, large-scale insights into surface indicators and subsurface potential (Sheffield et al., 2018). By integrating thematic datasets such as geology, lineament density, drainage, slope, rainfall, and land use into weighted overlay or multi-criteria decision-making models, RS and GIS provide robust groundwater potential zonation maps (Thapa et al., 2017; Díaz-Alcaide & Martínez-Santos, 2019). These techniques are frequently val-

idated with geophysical methods, particularly vertical electrical sounding (VES) and 2D resistivity imaging, to enhance reliability in heterogeneous basement terrains (Ezeamaka et al., 2022).

Recent studies in Africa, particularly within Nigeria's Basement Complex, have emphasized the importance of integrating RS, GIS, and resistivity surveys for groundwater assessment (Ejebu et al., 2022; Mangs et al., 2023). This integrated approach has proven effective in delineating groundwater potential zones, reducing exploration uncertainty, and supporting sustainable water resource development in regions facing acute water scarcity. Nevertheless, challenges remain, including data quality, validation gaps, and site-specific variability, underscoring the need for continued refinement of integrated hydrogeological mapping frameworks. How can a comprehensive approach integrating GIS, remote sensing, and Analytical Hierarchy Process (AHP) techniques contribute to the identification and mapping of groundwater potential zones for sustainable water resource management, considering the challenges of direct observation and traceability of groundwater, and how could this methodology be extended to regional and national levels for accurate groundwater potential mapping and zoning in the six area councils of Federal Capital Territory (FCT) Abuja, Nigeria?

The research gap identified is not that groundwater mapping has never been done; the gap is that it has not been done comprehensively, systematically, and regionally for FCT using a validated RS, GIS and AHP framework. The present study addresses the identified research gap by developing a comprehensive RS, GIS and AHP-based groundwater potential mapping framework for the six Area Councils of FCT

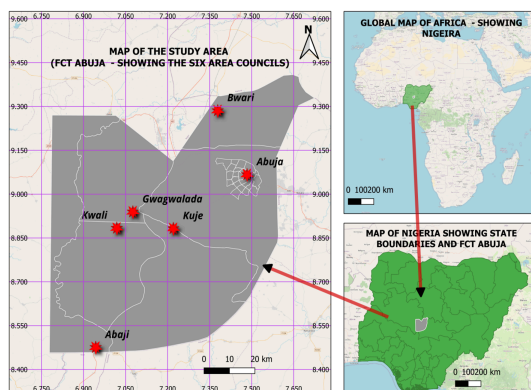


Fig. 1. Federal Capital Territory Abuja.

Abuja, integrating hydrogeological parameters, structural controls, and geophysical validation to produce a scientifically consistent, region-scale decision-support model adaptable for broader application in Nigeria's Basement Complex terrain.

2. The Study Area

FCT is located at an elevation of 360 meters (1,495.7 feet) above sea level, is characterized by a tropical wet-and-dry climate, designated as Aw in the Köppen classification. Annual precipitation is estimated at 122.12 millimeters (4.81 inches), distributed over roughly 145 days, which represents about 39.83% of the year (Adaji et al., 2019). The rainy season in this region typically extends from April to October, with annual rainfall ranging between 305 to 762 mm. In contrast, the dry season, characterized by the harmattan winds, generally spans from October or November to March or April, although occasional, sparse rainfall may occur during this period (Olugbenga & Osiewundo, 2015). Temperatures within the FCT generally remain warm throughout the year, with average monthly values around 27.5 °C, and daytime highs typically ranging from 25 to 30 °C, though they can reach up to 40°C dur-

ing the dry season (Ifediegwu, 2022) (Adaji et al., 2019).

3. Geology of the Area

The study area is part of the Basement Complex in North-Central Nigeria, which mainly consists of granite, granite-gneiss, and gneiss. These rocks often weather into reddish sandy clay or clay, usually containing mica flakes and covered by lateritic caps. While basement rocks are usually not good aquifers, their ability to store and transmit groundwater improves when they are fractured or deeply weathered (Omeje et al., 2013). The geology of FCT has been extensively documented by earlier researchers such as Oyawoye (1972) and McCurry (1976), who reported that the dominant lithologies include granites, gneisses, mica schists, hornblende- and feldspathic schists, as well as migmatites. The rocks are characterized by intense fracturing and jointing, with two principal fracture orientations trending NE–SW and NW–SE. These structural features exert significant control over the drainage network and river flow patterns in the region. In this area, vertical electrical sounding (VES) shows that the rocks are extensively weathered and have a high fracture index, both of

which help groundwater storage and movement. Earlier studies confirm that in basement complex regions, weathering and fracturing are the main ways groundwater can move (Olasehinde et al., 2016). Geological and structural controls have a significant influence on groundwater occurrence in the region. Fractures, faults, and outcrops often act as both barriers and conduits, shaping groundwater storage and movement by enhancing retention from surface infiltration (Jasrotia et al., 2013; Jasrotia, Kumar, & Singh, 2016).

Field investigations in comparable basement terrains across Nigeria report a wide range of lithologies, including quartzites, quartz schists, biotite schists, and granitic intrusions, all of which bear evidence of extensive Pan-African metamorphism and deformation (Adeoti & Okonkwo, 2016). Within such basement terrains, groundwater predominantly occurs in the weathered mantle and in fracture networks of fresh bedrock, reinforcing the importance of structural geology in hydrogeological assessments (Olugbenga & Osiewundo, 2015).

4. Methodology

4.1 Derivation of the thematic layers

The preparation of thematic layers was carried out through digital image processing of remote sensing data, digitization of existing maps, and integration of field observations to extract relevant information. To delineate groundwater potential zones within the study area, multiple thematic layers were generated using satellite imagery, Digital Elevation Models (DEM), and available maps and datasets, complemented by field validation through Remote Sensing and GIS techniques. The thematic layers derived are Rainfall, Geology, Slope, Drainage Density, Land Use/Land Cover,

Lineament Density, Topographic Wetness Index and Soil. These layers were then analysed using ArcGIS10.7.1 software and weights were assigned before delineating the groundwater potential zones.

4.2 Slope calculation

Slope gradient constitutes a critical parameter in identifying suitable locations for artificial groundwater recharge, as it directly governs surface water infiltration capacity (Selvam et al., 2015). In areas characterized by steep slopes, recharge potential is generally limited because runoff velocity is high, reducing the residence time required for effective infiltration (Machwal et al., 2011). Conversely, gently sloping terrains enhance groundwater recharge by promoting increased water retention and prolonged infiltration of rainfall into the subsurface.

The slope of the terrain was calculated using the SRTM DEM in ArcGIS 10.7.1. The Slope tool was employed to derive the slope in degrees. The slope is essentially the steepness or inclination of the terrain and was computed by determining the maximum rate of elevation change between each pixel and its neighbours. The equation used to compute the slope is:

$$Slope = \arctan \frac{\Delta Z}{D}, \quad (4.1)$$

where ΔZ is the change in elevation and D represents the horizontal distance between two points. This process produces a raster file in which each cell value represents the slope at that location, allowing for a detailed understanding of the terrain's steepness across the study area. This approach follows the principles outlined by Burroughs & McDonnell (1999).

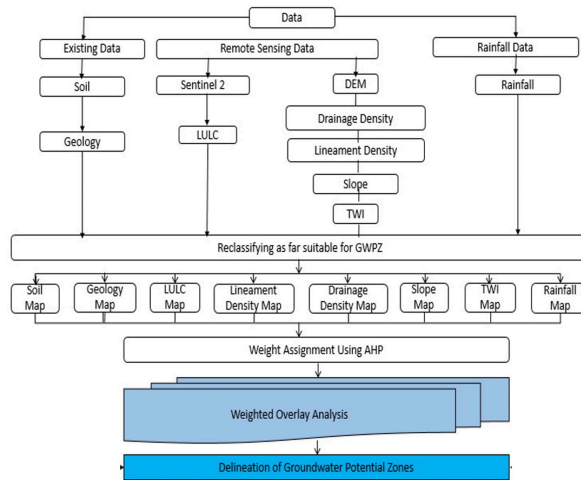


Fig. 2. Flowchart of the methodology.

4.3 Drainage density

Drainage density represents the total cumulative length of streams of all hierarchical orders per unit area within a drainage basin (Shekhar and Pandey, 2015). Drainage density exhibits a strong relationship with groundwater recharge, as recharge potential is closely influenced by surface permeability and runoff characteristics (Krishnamurthy et al., 1996; Magesh et al., 2012).

The drainage density calculation also utilized the SRTM DEM in ArcGIS. First, the DEM was filled using the Fill tool to remove any spurious depressions. Next, the Flow Direction tool was applied to derive the flow direction across the terrain, followed by the Flow Accumulation tool to identify areas of high-water accumulation. A threshold value (500 or above) was set to define the drainage network, which was then converted into a vector stream network using the Raster to Polyline tool. Finally, the Kernel Density tool was used to calculate drainage density, which expresses the total length of streams per unit area using

the formula:

$$Dd = \frac{L}{A}, \quad (4.2)$$

where Dd is the drainage density, L is the total length of streams, and A is the area of the watershed. This methodology is rooted in the hydrological principles described by Horton (1945).

4.4 Lineament density

Lineaments are prominent linear features observable on the Earth's surface that reflect underlying structural discontinuities within the bedrock and represent geomorphic expressions of crustal weaknesses such as faults, major fractures, joint systems, lithological boundaries, and aligned drainage patterns. They delineate zones of enhanced secondary permeability and porosity, which are critical for groundwater occurrence and movement, particularly in fractured basement terrains where primary porosity is negligible (Sankar, 2002). Areas characterized by high lineament density, especially at intersection zones, are widely recognized as favourable groundwater potential zones due to increased fracture connectivity and storage capacity. Moreover,

the convergence of fracture systems with topographically low-lying areas further enhances aquifer development by promoting infiltration and groundwater accumulation. Lineaments are typically extracted from remotely sensed imagery through visual or digital interpretation based on spatial variations in tone, texture, colour, and structural alignment, making them a vital thematic layer in hydrogeological investigations (Kumar & Kumar, 2010).

Lineaments are linear or curvilinear surface features that represent both simple and complex geological structures, including faults, fractures, and other discontinuity planes, which can be identified through remote sensing techniques (O'Leary et al., 1976). They are hydrogeologically significant, as they delineate zones of structural weakness that facilitate groundwater infiltration and subsurface flow, thereby serving as critical conduits for groundwater movement (Abdalla, 2012).

Lineament density was computed using a combination of hillshades and lineament extraction techniques. First, hillshades were generated in ArcGIS with a sun altitude of 45° and azimuths of 0°, 45°, 90°, and 135°. These hillshades were then overlaid to enhance linear features on the landscape, which represent potential lineaments. Lineaments were extracted using the line algorithm in PCI Geomatica, which identifies linear features based on changes in pixel intensity. The extracted lineaments were then processed in ArcGIS, and their density was calculated using the Kernel Density tool, following a similar approach to drainage density:

$$Ld = \frac{L}{A}, \quad (4.3)$$

where Ld is lineament density, L is the total length of lineaments, and A is the area of the

study area.

4.5 Topographic Wetness Index (TWI)

Beven and Kirkby (1979) introduced an algorithm for estimating spatial patterns of soil water deficit using topographic attributes and soil hydraulic properties. However, accurately identifying saturated zones remains challenging due to limited data availability and incomplete understanding of hydrological processes operating from plot to catchment scales. Modeling soil moisture distribution in space and time typically requires highly parameterized approaches that represent these governing processes (Mansour and Chaubey, 2009; Qin et al., 2009). As an alternative, terrain-based indices have been employed to delineate potential saturated areas and water harvesting sites by incorporating key controlling factors (Ruhoff et al., 2011). In this context, the steady-state Topographic Wetness Index (TWI) was utilized to depict the spatial distribution of surface water accumulation and flow. TWI, derived solely from topographic variables, is a function of upslope contributing area and local slope gradient (Grabs et al., 2009; Qin et al., 2009), and is computed from widely available DEM data using spatial analysis tools in ArcGIS.

The Topographic Wetness Index (TWI) is a hydrological index that represents the spatial distribution of soil moisture. It was computed using the SRTM DEM in ArcGIS. First, the Slope tool was applied to calculate slope, and the Flow Accumulation tool was used to determine upslope contributing areas. The TWI was then calculated using the following equation:

$$TWI = \ln \left(\frac{\alpha}{\tan \beta} \right), \quad (4.4)$$

where α is the upslope contributing area derived from the flow accumulation raster, and β is the slope angle in radians. This formula indicates that areas with a higher upslope contributing area and lower slope values tend to have higher TWI, making them more prone to moisture accumulation. The TWI was generated using the Raster Calculator in ArcGIS, following the theoretical framework provided by Sørensen, Zinko & Seibert (2006).

The Specific Catchment Area (a) represents the upslope area draining toward a specific cell or point, typically derived from Digital Elevation Models (DEMs). Its calculation depends on the flow algorithm employed: single-direction flow routes the accumulated area along the steepest downslope path, while multi-directional flow distributes flow among multiple downslope cells based on slope gradients, offering greater accuracy in certain terrains. Higher TWI reflects regions with a large upslope contributing area and gentle slopes, which tend to accumulate water and exhibit higher soil moisture levels. Lower TWI corresponds to areas with a smaller contributing area or steeper slopes, usually characterized by drier conditions and better drainage.

4.6 Rainfall

Rainfall constitutes the primary source of groundwater recharge, as it controls the volume of water available for infiltration into the subsurface system (Aggarwal et al., 2013). Slope is a critical topographic parameter influencing groundwater occurrence; relatively flat terrains promote water retention and enhance infiltration, whereas steep slopes accelerate surface runoff, thereby reducing recharge potential (Sisay, 2007).

The monthly rainfall data for twelve months downloaded were added together to

derive the annual rainfall map of the study area.

4.7 Land use/ land cover

Land use and land cover patterns within a given area are largely governed by geomorphological setting, agro-ecological conditions, climatic influences, and anthropogenic activities, and they constitute a significant factor controlling groundwater occurrence and availability Hussein et al., 2017). Singh (2014) emphasized that land use/land cover (LULC) characteristics play a critical role in regulating groundwater storage and recharge processes. The relative influence of LULC types on groundwater potential, in increasing order, was identified as grazing land > cultivated land > shrubland > plantation. Shrubland and plantation areas are therefore considered more favorable for groundwater occurrence due to enhanced infiltration capacity. Furthermore, intensive cultivation patterns are commonly associated with zones of high groundwater potential, reflecting the availability of accessible subsurface water resources.

The FCT LULC was extracted using clipping tools from the Nigeria LULC map.

4.8 Geological map

The study area is situated within the Basement Complex of North-Central Nigeria, dominated by granites, granite-gneiss, gneiss, mica schists, hornblende- and feldspathic schists, and migmatites, as documented by Oyawoye (1972) and McCurry (1976). These crystalline rocks commonly weather into reddish sandy clay or clayey regolith with lateritic caps. Although basement rocks generally exhibit low primary porosity, groundwater storage and transmission are significantly enhanced through deep weathering and intense frac-

turing (Omeje et al., 2013). The region is structurally characterized by prominent NE–SW and NW–SE fracture orientations, which influence drainage patterns and sub-surface flow. Vertical electrical sounding (VES) investigations reveal substantial weathering and high fracture indices, confirming that groundwater occurrence is largely controlled by secondary porosity (Olasehinde et al., 2016). Fractures, faults, and outcrops may function as both conduits and barriers to flow (Jasrotia et al., 2013; Jasrotia, Kumar, & Singh, 2016). Comparable Basement terrains across Nigeria exhibit similar Pan-African metamorphic features and fracture-controlled aquifer systems (Adeoti & Okonkwo, 2016; Olugbenga & Osiewundo, 2015).

The geological map obtained from NGSA was digitized, and rock types were extracted from it.

4.9 Soil map

The characterization of soil cover is a fundamental component in the delineation of groundwater recharge potential zones (Punmia and Jain, 2005). The capacity of surface water to infiltrate and subsequently recharge an aquifer system is strongly influenced by soil properties, including texture, depth, drainage characteristics, infiltration rate, and overall water transmission capacity (Viessman et al., 1989).

Using the clipping tool, the soil map of FCT was extracted from the FAO soil map.

5. The Analytic Hierarchy Process (AHP)

The AHP process commences with the following steps:

Identification of influencing factors pertinent to a specific decision-making scenario.

Comparison of each factor against every other factor, assigning values from Saaty’s 1 to 9 scale (refer to Table 1, Table 2) to denote their relative priority concerning the potential zone.

Organization of these values in a matrix format to facilitate the determination of the priority vector.

5.1 Computation of normalized weights based on the priority vector

Evaluation of eigenvalue and Consistency Index using Eq. (5.1).

Table 1. Saaty’s 1–9 Scale of Relative Importance (Saaty 1980).

Scale	Importance
1	Equal importance
2	Weak importance
3	Moderate importance
4	Moderate plus importance
5	Strong importance
6	Strong plus importance
7	Very Strong importance
8	Very, Very Strong importance
9	Extreme importance

Table 2. Saaty’s Ratio Index for Different Values of ‘n’ (Saaty 1980).

N	RI
1	0
2	0
3	0.58
4	0.89
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49

RI = RCI = Random Consistency Index

5.2 Consistency Index (CI)

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (5.1)$$

where λ_{max} is the largest maximum eigenvalue of the comparative matrix and n = number of factors (thematic layers used) and = average value of the consistency vector.

5.3 Consistency Ratio (CR)

Consistency Ratio (CR) is a measure of consistency of the pairwise comparison matrix.

$$CR = \frac{CI}{RI}, \quad (5.2)$$

where RI is the Ratio Index; The value of RI for different n values is given in Table 2. $Forn = 8, RI = 1.41$.

5.4 Delineation of the groundwater potential zones

To generate the groundwater potential zone map of the study area, all seven thematic layers would be integrated using the weighted overlay analysis function within the ArcGIS platform. This integration will be performed according to the following equation:

$$\begin{aligned} GWPI = \sum [& (RF_w \times RF_{wi}) \\ & + (Geol_w \times Geol_{wi}) \\ & + (SL_w \times SL_{wi}) + (DD_w \times DD_{wi}) \\ & + (LD_w \times LD_{wi}) + (ST_w \times ST_{wi}) \\ & + (LU_w \times LU_{wi}) + (TWI_w \times TWI_{wi})], \end{aligned} \quad (5.3)$$

where $GWPI$ refers to groundwater potential index, RF stands for Rainfall, $Geol$ for Geology, SL for slope, DD for Drainage Density, LD stands for Lineament Density, ST for soil type, LU for land use land cover,

and TWI for Topographic Wetness Index. The subscripts "w" and "wi" denote the normalized weight of a thematic layer and individual features, respectively. The resulting groundwater potential zone map will be categorized into zones representing low, moderate, high, and very high potential.

5.5 FCT stream network

The drainage network of the Federal Capital Territory exhibits a well-developed dendritic pattern with stream orders ranging from first to fifth order, reflecting the influence of relatively homogeneous crystalline lithologies of the Nigerian Basement Complex. The predominance of first- and second-order streams across the area indicates numerous headwater channels that function as potential groundwater recharge zones, while higher-order streams represent integrated drainage pathways that act as regional discharge zones. The spatial distribution of the drainage hierarchy suggests that groundwater flow generally follows the regional topographic gradient from upland areas toward major river channels such as the Usuma River and the Gurara River. In basement terrains, watershed boundaries often approximate groundwater basin limits; therefore, the drainage framework provides a practical basis for delineating hydrogeological sub-basins within the study area. Integrating basin-scale drainage characteristics into groundwater potential modeling improves the physical realism of the analysis by ensuring that recharge, subsurface flow, and discharge processes are evaluated within their natural hydrological boundaries. Consequently, the drainage basin structure constitutes a fundamental control on groundwater occurrence and distribution in the FCT.

6. Results and Discussions

6.1 Slope and groundwater potential

Slope, as a geomorphological factor, influences groundwater recharge by affecting infiltration. Gentle slopes promote infiltration and recharge due to reduced runoff, whereas steep slopes increase runoff and limit infiltration, thereby indicating variations in an area's groundwater potential (Fashae et al., 2014).

In slope in the FCT Abuja watershed, was categorized into five classes using the spatial analyst tool in ArcMap 10.7.1 (Fig. 3). The influence of slope on groundwater potential is closely tied to its impact on surface runoff and infiltration, with slope ranges reflecting the terrain's steepness and recharge capacity. Low slopes (0–3.38) are flat or gently sloping, promoting high infiltration and good groundwater recharge potential. Moderate slopes (3.38–7.32) exhibit slightly increased runoff but retain significant infiltration, offering moderate recharge potential. Transitional slopes (7.32–13.52) present a balance between runoff and infiltration, with reduced recharge potential influenced by additional factors like soil type and vegetation. Steep slopes (13.52–21.70) experience faster runoff, minimal water retention, and low recharge potential. Very steep slopes (21.70–71.86) are dominated by rapid runoff, negligible infiltration, and are generally unsuitable for groundwater exploration. To illustrate the inverse relationship between slope and groundwater productivity (Yeh, Cheng, Lin, & Lee, 2016), the most gentle slope class (0 – 3.38 °) was assigned the highest weight of "5," while the steepest slope class (21.70 ° - 71.86 °) received the lowest weight of "1."

The slope is a factor that regulates the movement of water below the surface. It in-

fluences the flow of water across the land and its infiltration into the soil, thereby affecting groundwater replenishment within a watershed (Berhanu & Hatiye, 2020).

Gentle slopes generally facilitate greater infiltration and longer residence times for surface water, thereby increasing the potential for groundwater recharge. In contrast, steep slopes lead to rapid runoff and reduced infiltration (Tabassum et al., 2025). Consequently, regions characterized by gentle slopes are considered to possess higher groundwater potential due to extended water retention, in contrast to steep terrains where rapid runoff curtails infiltration opportunities (Ifediegwu, 2022).

The slope classes of the FCT (Table 3) watershed reveal a predominantly steep to very steep terrain. The largest portion of the area falls under the very steep slope class (21.70–71.86°), covering 4008.86 km² (50.31%), followed by the steep slope class (13.52–21.70°) with 2474.98 km² (31.06%). Collectively, these two classes account for over 81% of the total area, indicating that the watershed is largely dominated by steep topography with high runoff potential and limited infiltration.

Table 3. Slope classification in FCT Abuja.

Sn	Slope (Degree)	Area (km ²)	Coverage (%)	Classes
1	0 - 3.38	182.32	2.29	Low
2	3.38 - 7.32	451.52	5.67	Moderate
3	7.32 - 13.52	850.51	10.67	Transitional
4	13.52 - 21.70	2474.98	31.06	Steep
5	21.70 - 71.86	4008.86	50.31	Very Steep

The transitional slope class (7.32–13.52°) occupies 850.51 km² (10.67%), serving as an intermediate zone where both runoff and infiltration processes occur, though recharge potential remains moderate. Meanwhile, moderate slopes (3.38–7.32°) cover 451.52 km² (5.67%), and the low slope class (0–3.38°) represents the

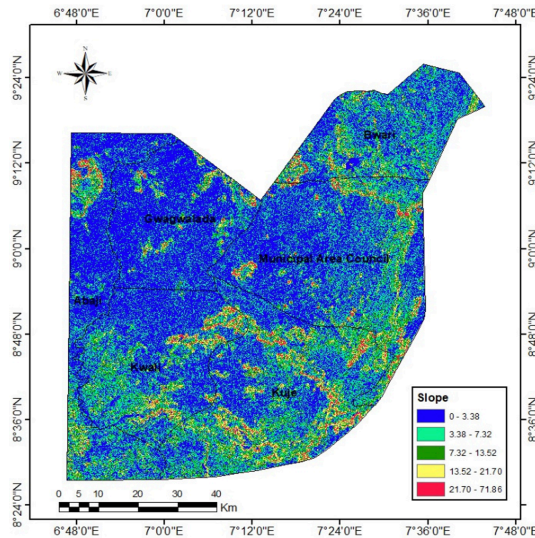


Fig. 3. Slope map of FCT Abuja.

smallest proportion, 182.32 km² (2.29%). These two categories, though limited in their areal extent, are critical for groundwater recharge, as they favour infiltration and longer water residence times.

Terrain slope significantly influences groundwater recharge. Flat or gently sloping areas promote water accumulation and infiltration into the subsurface, enhancing groundwater recharge potential. Conversely, as the slope increases, runoff becomes more dominant, reducing infiltration and resulting in lower groundwater potential. Lower slopes facilitate water retention, while steeper slopes favour rapid runoff, limiting recharge capacity. Slope also reflects the area's topographic structure, connecting local and regional relief and indicating the general direction of groundwater flow, thereby affecting recharge and discharge patterns.

For this study, slope data derived from SRTM DEM and represented in degrees using ArcMap provided critical insight into groundwater dynamics (Oluibukun et al., 2022); (Liu, Yan, &

Guan, 2025)

6.2 Drainage density and groundwater potential

Drainage density (Dd), which is the total stream length per unit area, reveals the hydrological and geological characteristics of a region. The study area has five classes of DD (Fig.4), ranging from very low to very high. Very low drainage density (0.09–0.74) indicates well-drained areas with permeable soils, gentle slopes, and a high groundwater recharge potential, making them ideal for agriculture and water retention. Low drainage density (0.74–0.95) indicates a balance between runoff and infiltration, supporting sustainable agricultural and forest practices. Moderate drainage density (0.95–1.14) suggests a mix of runoff and infiltration, requiring erosion control for mixed land use. High drainage density (1.14–1.35) indicates poor drainage with limited infiltration, which increases erosion and flood risks. In contrast, very high drainage density (1.35–2.10) reflects runoff dominance in impermeable or steep

terrains, necessitating soil conservation and flood mitigation measures. Effective management relies on understanding local geology, climate, and vegetation to address these varying conditions.

A negative relationship exists between drainage density and groundwater recharge in a region, as high drainage densities reduce infiltration rates (Pinto et al., 2017). This inverse relationship implies that areas with a lower drainage density are more conducive to groundwater accumulation, making them prime candidates for groundwater potential zones (Ajayi et al., 2022). Conversely, regions characterized by elevated drainage densities tend to exhibit diminished groundwater potential due to increased surface runoff and reduced percolation into the subsurface (Ajayi et al., 2022; Tabassum et al., 2025).

This phenomenon is attributed to the accelerated removal of surface water, which curtails the residence time available for water to infiltrate porous media, thereby limiting groundwater replenishment (Ajayi et al., 2022).

Drainage density, defined as stream length per watershed area, reflects drainage efficiency and influences groundwater potential. Low drainage density favors infiltration and recharge, enhancing groundwater availability, while high drainage density accelerates runoff, reducing infiltration. Thus, regions with low drainage density are generally more suitable for groundwater development compared to areas with dense stream networks (Raj et al., 2024).

The drainage density in the study area ranges from 0.09 to 2.10 km/km², reflecting variations in the concentration of drainage networks. The highest area coverage of 28.69% falls within the 0.95–1.14 km²/km² range, suggesting that a large portion of the terrain is characterized by a mod-

erate density of drainage channels.

Similarly, 26.38% of the area falls within the 1.14–1.35 km²/km² range, indicating that a substantial part of the landscape has moderate to slightly higher drainage density (Table 4).

Table 4. Drainage density classification in FCT Abuja.

Sn	Drainage Density (km/km ²)	Area (km ²)	Coverage (%)	Classes
1	0.09 – 0.74	854.91	10.71	Very High
2	0.74 – 0.95	1820.76	22.82	High
3	0.95 – 1.14	2289.56	28.69	Moderate
4	1.14 – 1.35	2105.03	26.38	Low
5	1.35 – 2.10	909.43	11.40	Very Low

Areas with low drainage density, ranging between 0.09 and 0.74 km/km², account for 10.71% of the coverage. These zones reflect relatively sparse drainage channels, which are typical of regions with less surface runoff and soils that may be either more resistant to erosion or more permeable, thereby favouring infiltration.

On the other hand, regions with high drainage density, ranging from 1.35 to 2.10 km/km², account for 11.40% of the study area. Such zones are characterized by dense stream networks, which promote higher surface runoff while limiting infiltration; these conditions can negatively influence groundwater recharge.

Areas with lower drainage density are more favourable for groundwater recharge, as runoff is reduced. In contrast, zones with higher drainage density may experience increased runoff and erosion risks, which could impact both groundwater quality and availability. Therefore, identifying regions with lower drainage density is critical for effective groundwater management strategies, as these areas often exhibit enhanced infiltration rates and a greater capacity for aquifer replenishment (Lawal et al., 2021). This approach is particu-

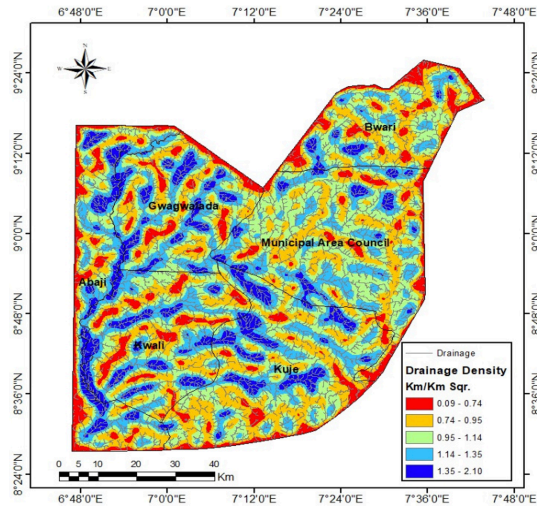


Fig. 4. Drainage density map of FCT Abuja.

larly valuable in arid and semi-arid regions where water scarcity is a prevalent issue, making efficient groundwater recharge crucial for sustainable water resources management (Shamkhi, 2021).

The dataset from FCT suggests a landscape with predominantly moderate drainage densities, where a significant portion of the area experiences balanced surface water flow, which in turn influences recharge, erosion, and land management strategies. Areas with very low or high drainage densities occupy smaller proportions, indicating heterogeneous surface hydrology across the region. This variability underscores the intricate interplay between topographic characteristics, such as slope and lithology, and hydrologic processes, which collectively determine the efficiency of water movement across the terrain (Boothroyd et al., 2023). Conversely, high drainage densities are typically associated with fine drainage textures and a higher susceptibility to flooding, reflecting rapid surface runoff and reduced infiltration (Kandekar et al., 2021). Moreover, low drainage density often correlates with

increased infiltration rates, which can mitigate peak discharges and reduce overall runoff, as observed in some watershed studies (Arulbalaji & Gurugnanam, 2017).

This relationship highlights the significance of drainage density as a crucial indicator for evaluating both groundwater potential and flood risk. Lower densities typically signify favourable conditions for groundwater recharge, while higher densities indicate increased flood susceptibility due to efficient surface runoff (Kotb et al., 2024).

6.3 Lineament Density (km/km^2) and groundwater potential

Lineament density refers to the concentration of linear features, including faults and fractures, within a given area. These features typically act as pathways for groundwater flow and storage, with higher lineament densities often associated with increased groundwater potential. The presence of structural discontinuities, such as faults and fracture planes, can be identified in digital elevation models as linear features, which often correspond to areas of in-

creased water infiltration and storage (Rios-Sanchez et al., 2012). Specifically, areas with higher lineament density, particularly those trending NW-SE to N-S, act as preferred pathways for groundwater flow, enhancing infiltration and increasing the likelihood of encountering productive aquifers (Mohamed, 2015).

In this research, the lineament density map of FCT (Fig. 5) shows that areas with very low lineament density (0–0.30) cover approximately 22.24%. Low lineament density (0.30–0.61) zones occupied about 21.75%. exhibit moderate structural stability with slightly improved infiltration and moderate groundwater recharge potential. are structurally stable with limited infiltration pathways, making them more suitable for surface water storage than groundwater development. Similarly, areas with low lineament density tend to limit water flow and storage, resulting in lower groundwater potential. Lineaments reflect underlying structural characteristics, including fractures and faults, and often appear as linear or gently curved patterns, differing from adjacent geological formations (O’Leary, Friedman, & Pohn, 1976).

Moderate lineament density (0.61–0.90) occupied about 23.80% of the study area (see Table 5). Moderate lineament density areas are characterized by increased fracturing, which enhances groundwater movement and recharge, and represent a balance between structural integrity and permeability. As balanced lineament density is crucial for optimal groundwater potential, regions exhibiting a moderate density are often prioritized for water resource development (Ifediegwu, 2022). This is because an overabundance of fractures might accelerate subsurface flow, reducing residence time for infiltration, while extremely low densities impede the hydraulic conduc-

tivity necessary for significant aquifer formation (Salih & Al-Manmi, 2021). Moreover, the geometric arrangement and interconnectedness of these lineaments within a moderate density framework also play a pivotal role in dictating the anisotropic flow paths and storage capacity of groundwater (Gupta & Srivastava, 2010).

Table 5. Drainage density classification in FCT Abuja.

Sn	Drainage Density (km/km ²)	Area (km ²)	Coverage (%)	Classes
1	0.09 – 0.74	854.91	10.71	Very High
2	0.74 – 0.95	1820.76	22.82	High
3	0.95 – 1.14	2289.56	28.69	Moderate
4	1.14 – 1.35	2105.03	26.38	Low
5	1.35 – 2.10	909.43	11.40	Very Low

High lineament density (0.90–1.17) zones covered about 19.76% of FCT. They are highly fractured, offering significant pathways for recharge and aquifer connectivity, making them prime targets for groundwater development but prone to surface contamination. Regions characterized by high lineament density are associated with enhanced water circulation and, consequently, greater groundwater potential, making them favorable for groundwater exploration (Ifediegwu, 2022).

A very high lineament density (1.17–1.64) zone occupied about 12.45% of FCT. High-lineament density areas are intensely fractured regions that exhibit excellent recharge potential and rapid groundwater flow, potentially reaching deeper aquifers, but are also vulnerable to overexploitation and pollution. Consequently, groundwater exploration should prioritize moderate to very high-density zones, while also addressing contamination risks in highly fractured regions. Conversely, regions characterized by high lineament density often correlate with increased fracturing and faulting, providing significant pathways for

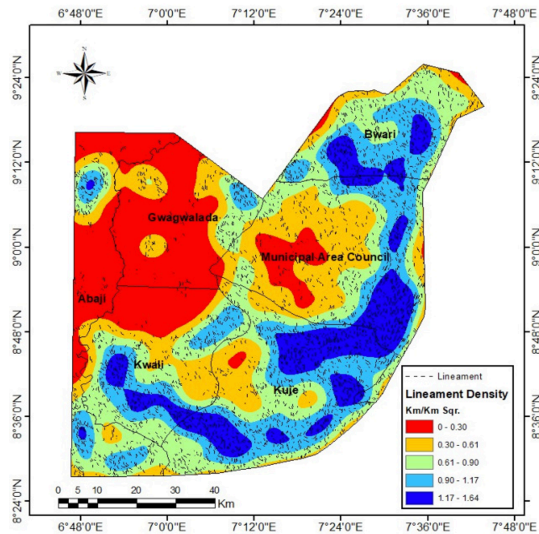


Fig. 5. Lineament density map of FCT Abuja.

groundwater infiltration and enhanced storage capacity (Berhanu & Hatiye, 2020). This relationship suggests that areas with higher lineament density are typically more favourable for groundwater exploration and development due to increased permeability and storage within fractured rock systems (Gupta & Srivastava, 2010; Abdullateef et al., 2021).

The greater presence of fractures in these areas enhances water infiltration and subsurface movement, supporting groundwater recharge. These fractured zones serve as critical conduits for groundwater flow, particularly in basement complex rocks, which are otherwise not aquiferous (Ajayi et al., 2022).

6.4 Topographic Wetness Index (TWI) and groundwater potential

The Topographic Wetness Index (TWI) is a quantitative metric that estimates the potential for water accumulation in a landscape, reflecting the influence of topography on hydrological processes by integrating slope and the upstream

contributing area. It is widely employed as a proxy for soil moisture and as an indicator of saturated areas, playing a crucial role in understanding hydrological and ecological patterns across diverse terrains (Winzeler et al., 2022). TWI is vital for assessing groundwater potential, evaluating wetland mapping, and modelling flow routing in various landscapes, including permafrost wetlands, where topography significantly influences hydrological behaviour despite low magnitudes (Jhariya et al., 2016; Bartels et al., 2018; Persson et al., 2012). Specifically, the TWI is instrumental in characterizing biological processes, such as annual net primary production and vegetation patterns, as well as mapping the spatial dynamics of soil properties to understand landscape physicochemical processes and land-use changes (Sørensen et al., 2006). However, despite its widespread application, the traditional TWI can present limitations in dynamic hydrological contexts due to its static nature (Li et al., 2020). This static characteristic limits its utility in capturing transient hydrological

phenomena and necessitates the exploration of more dynamic approaches for comprehensive environmental modelling (Ågren et al., 2021; Ndhlovu & Woyessa, 2021).

The TWI analysed in FCT in this research (see Fig. 6) was classified into five zones (Table 6). Zones with very low TWI (2.35–6.53) covering about 34.13% of FCT, correspond to steep slopes or limited contributing areas, characterized by poor water accumulation and minimal suitability for groundwater recharge.

Low TWI (6.53–8.07) regions occupied approximately 38.80% of the FCT, with gentler slopes, and exhibit a moderate water retention potential, supporting limited groundwater recharge. Areas with low TWI values indicate flatter terrains and larger upslope contributing areas, suggesting increased soil moisture and favourable conditions for groundwater recharge (Grabs et al., 2009; Winzeler et al., 2022). Moreover, the presence of densely vegetated areas often correlates with lower TWI values, facilitating enhanced infiltration and contributing to higher groundwater potential (Tabassum et al., 2025). Therefore, integrating TWI with other hydrogeological factors can provide a more robust assessment of groundwater recharge potential across diverse landscapes (Rodríguez-Moreno & Gunter, 2025).

Moderate TWI (8.07–10.34) zones occupied approximately 17.22% of the FCT, demonstrating balanced conditions conducive to groundwater recharge and agricultural activities reliant on soil moisture.

High TWI (10.34–13.6), occupying approximately 7.61% of the FCT, reflects flatter terrain or larger contributing areas with enhanced water accumulation, suitable for groundwater recharge, surface wa-

ter storage, and moisture-reliant agriculture.

Table 6. Topographic Wetness Index (TWI) classification in FCT Abuja.

Sn	TWI	Area (km ²)	Coverage (%)	Classes
1	2.35 – 6.53	2579.16	34.13	Very Low
2	6.53 – 8.07	2931.34	38.80	Low
3	8.07 – 10.34	1301.19	17.22	Moderate
4	10.34 – 13.60	575.20	7.61	High
5	13.60 – 25.64	169.18	2.24	Very High

Very high TWI (13.6–25.64) covers about 2.24% of FCT, characterizing low-lying, flat areas with maximum water accumulation, which supports wetlands and aquifer recharge but poses risks of waterlogging and stagnation in poorly drained soils. High TWI values indicate areas of convergence and gentle topography, which are conducive to significant water accumulation and thus represent favourable zones for groundwater storage and recharge (Grabs et al., 2009; Winzeler et al., 2022).

Moderate to very high TWI areas are ideal for water resource management, while low TWI zones require erosion control and infiltration enhancement. These findings are crucial for delineating groundwater potential zones, particularly when integrated with other thematic layers such as land use/land cover, geology, and rainfall, to produce comprehensive groundwater resource maps (Jhariya et al., 2016; Tabassum et al., 2025).

TWI helps locate saturated areas suitable for water harvesting and recharge. By reflecting the relationship between topography and moisture distribution, TWI provides critical insights for managing water flow and stagnation in landscapes (Berhanu & Bisrat, 2018). This index quantifies the propensity for water accumulation based on local slope and upstream contributing area, making it an essential tool for identifying

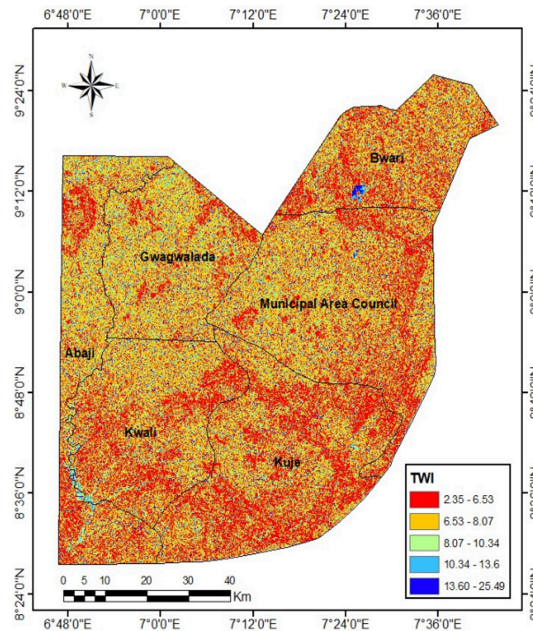


Fig. 6. Topographic Wetness Index (TWI) map of FCT Abuja.

groundwater potential zones (Persson et al., 2012).

6.5 Rainfall and groundwater potential

The highest rainfall is experienced in the NE around Bwari Area Council and some part of Abuja Municipal Area Council (AMAC) of about (1278-1353) mm/year. The lowest rainfall is experienced in the SW and NW parts around Kwali and Abaji Area Councils of about (1013-1087) mm/year (Fig.7 and Table 7).

Table 7. Topographic Wetness Index (TWI) classification in FCT Abuja.

Sn	Annual Rainfall (mm/year)	Area (km ²)	Coverage (%)	Classes
1	1013 – 1087	996.29	13.16	Low
2	1087 – 1153	2213.21	29.24	Moderate – Low
3	1153 – 1220	1991.03	26.30	Moderate
4	1220 – 1278	1159.39	15.31	High
5	1278 – 1353	1210.64	15.99	Very High

The annual rainfall distribution across the Federal Capital Territory (FCT), Abuja, shows notable spatial variation,

ranging from 1013 mm/year to 1353 mm/year. The lowest rainfall class (1013–1087 mm) covers 996.29 km², accounting for 13.16% of the total area (see Table 7), and represents zones with limited precipitation. This suggests restricted water availability and potentially lower groundwater recharge.

The moderate–low rainfall class (1087–1153 mm) occupies the largest proportion of land, covering 2213.21 km² (29.24%), followed by the moderate class (1153–1220 mm) with 1991.03 km² (26.30%). Together, these two classes dominate the rainfall pattern in Abuja, representing more than 55% of the area, indicating that most of the territory experiences rainfall within this middle range. Such regions likely support balanced agricultural activities and have a high potential for groundwater recharge.

On the higher end, the high rainfall class (1220–1278 mm) extends over

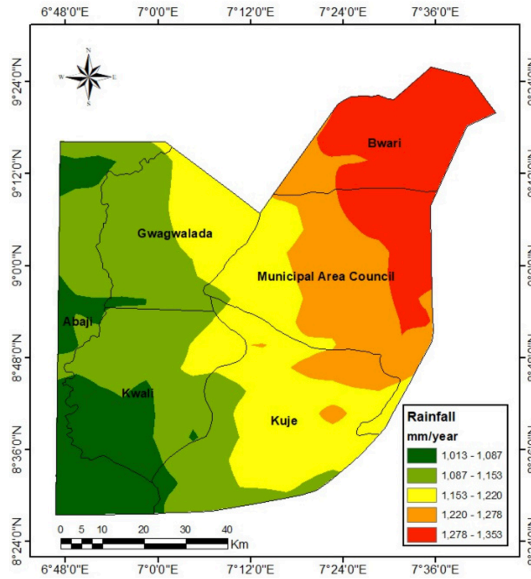


Fig. 7. Annual rainfall map of FCT Abuja (September 2023 – August 2024).

1159.39 km² (15.31%), while the very high class (1278–1353 mm) accounts for 1210.64 km² (15.99%). These areas represent zones of intense rainfall concentration, with a greater potential for surface water accumulation, increased infiltration, and potentially higher flood risks.

Generally, the rainfall distribution pattern indicates that while low rainfall zones are relatively limited, moderate to moderate–low classes dominate the FCT landscape. The high and very high rainfall zones together contribute nearly 31% of the area, showing significant potential for water resource availability. This classification highlights how rainfall variability influences hydrological balance, agricultural suitability, and groundwater recharge potential within the region.

Annual rainfall has a significant influence on groundwater potential, as it governs the availability of water for infiltration and recharge. Rainfall is a direct source of groundwater recharge; areas receiving higher amounts of rainfall have a

greater potential for groundwater recharge. The amount and timing of groundwater recharge are critically controlled by both hydrogeological and climatic factors, where increased rainfall directly correlates with enhanced recharge rates (Khatal et al., 2018). Areas with higher rainfall are more likely to experience significant groundwater recharge as more water is available to infiltrate into the subsurface. In contrast, areas with lower rainfall have reduced groundwater potential due to limited water availability for infiltration. Areas with higher rainfall are more likely to experience significant groundwater recharge as more water is available to infiltrate into the subsurface. In contrast, areas with lower rainfall have reduced groundwater potential due to limited water availability for infiltration. Specifically, the net balance between precipitation and evapotranspiration directly influences groundwater recharge, implying that climate variability plays a significant role in determining the amount of water available for aquifer replenishment (Tsypin

et al., 2024). This relationship is further complicated by the fact that the evaporative fraction of water increases with aridity, diminishing the amount of precipitation that ultimately contributes to streamflow and, by extension, groundwater recharge in drier climates (Berghuijs et al., 2022).

Higher rainfall ranges (High and Very High) generally enhance the potential for groundwater recharge and support sustainable extraction, whereas lower ranges (Low, Moderate-Low) necessitate careful management due to insufficient aquifer replenishment. Additionally, regions with high rainfall are vulnerable to contamination from rapid infiltration, especially in areas with porous soils. The management of excess rainfall in these areas requires infrastructure improvements to mitigate flooding and promote effective infiltration, thereby optimizing recharge. Furthermore, groundwater potential is influenced not only by rainfall but also by various hydrogeological factors, including soil type, geology, topography, and land use, which collectively affect the efficiency of recharge processes.

6.6 Land Use/Land Cover (LULC) and groundwater potential

The land use and land cover (LULC) composition described (see Fig. 8 and Table 8), built areas constitute 10.57%, bare ground is 0.02%, trees/crops/rangeland make up 88.85%, flooded vegetation is 0.01%, and water bodies account for 0.55%. This composition has several implications for groundwater potential in the area.

High Vegetative Cover, predominance of trees, crops, and rangeland (88.85%) suggests that the area has substantial vegetative cover, which can enhance groundwater recharge. Vegetation plays a crucial role in promoting infiltration through root systems, which helps to create

Table 8. Land Use/Land Cover Classification in FCT Abuja.

Sn	Land cover classes	Area (km ²)	Coverage (%)
1	Built area	846.79	10.57
2	Bare Ground	1.61	0.02
3	Trees/Crops/Rangeland	7120.82	88.85
4	Flooded Vegetation	0.94	0.01
5	Water	44.11	0.55

pathways for rainwater to percolate into the soil and replenish aquifers.

Minimal Impervious Surfaces of relatively low built area (10.57%) indicates a limited presence of impervious surfaces such as roads and buildings. This is beneficial for groundwater recharge, as less impervious surface area means reduced runoff, allowing more water to infiltrate the soil. However, it is important to note that some urban development can lead to increased demand for groundwater extraction.

Bare Ground with only 0.02% bare ground, there is minimal exposure of soil to erosion or runoff. This suggests a lower risk of surface soil degradation, which can otherwise inhibit recharge by creating compacted surfaces that reduce infiltration rates.

Flooded Vegetation and Water Bodies have minimal presence of flooded vegetation (0.01%) and water bodies (0.55%) indicates limited standing water, which may reduce risks of waterlogging and surface water contamination. However, if water bodies were more prevalent, they could provide additional recharge opportunities under certain conditions.

Potential for Contamination: While vegetation can protect groundwater quality, it is essential to manage agricultural practices within crop and rangeland areas to prevent contamination from fertilizers and pesticides that may leach into the groundwater.

Water Demand: The agricultural land use suggests a potential need for signifi-

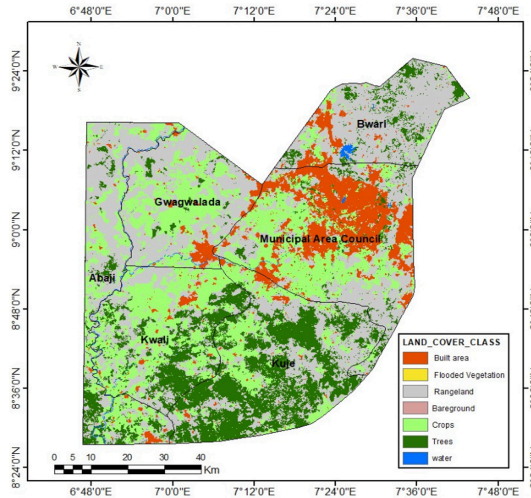


Fig. 8. Land Use/Land Cover (LULC) map of FCT Abuja.

cant water extraction for irrigation, which could strain groundwater resources if not managed sustainably. The balance between recharge and extraction is crucial for maintaining stable groundwater levels.

Generally, the LULC composition of the study area indicates a favourable environment for groundwater recharge due to the high percentage of vegetative cover and low levels of impervious surface.

Land use and land cover (LULC) have a significant influence on groundwater recharge. Built-up areas, with extensive impervious surfaces, hinder water infiltration and have lower groundwater potential. This is primarily due to the replacement of permeable surfaces with impervious ones, which reduces recharge and increases surface runoff (Ali et al., 2024). This alteration of natural hydrological pathways not only diminishes groundwater reserves but also exacerbates the potential for stormwater contamination of the remaining groundwater due to increased pollutant loads in surface runoff (Pitt, Clark, & Field, 1999). Conversely, natural landscapes with permeable soils and vegetation

facilitate greater infiltration, contributing positively to groundwater recharge (Wang et al., 2014). Urbanized regions, characterized by extensive impervious surfaces, typically exhibit significantly reduced infiltration rates, thereby minimizing groundwater recharge (Rane et al., 2023). Forested land supports consistent water flow and facilitates regular water percolation, whereas cultivated land impacts slope stability due to soil saturation beneath the vegetation cover (Elubid et al., 2020).

6.7 Geological map and groundwater potential

The geological formations in the study area influence groundwater potential, as different rock types vary in their ability to store and transmit water (Fig. 9).

Permeable rocks, such as sandstone, have high porosity and permeability, making them ideal for storing and recharging groundwater. On the other hand, certain granites and schists, which are less permeable, offer lower groundwater potential. Geological formations that contain fractures can enhance permeability and ground-

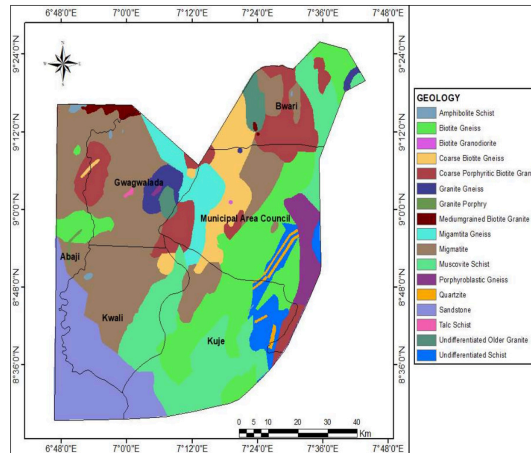


Fig. 9. Geological map of FCT Abuja.

water storage, contributing to higher potential. Granite formations generally exhibit moderate to low groundwater potential due to the absence of primary porosity, which limits their ability to function effectively as aquifers. However, when subjected to significant fracturing and weathering, their capacity to store and transmit water can improve substantially, enabling them to yield appreciable quantities of groundwater (Ejebu, 2020).

The Precambrian lithologies underlying the study area are characterized by aquifers with low to moderate groundwater yield potential. Cretaceous sediments exhibit higher productivity due to their intergranular permeability and the potential to form extensive aquifers (Adelana et al., 2008). In metamorphic terrains, the primary aquifers capable of storing and transmitting groundwater are predominantly regolith and fractures (Ejebu et al., 2017).

6.8 Soil type and groundwater potential

The soil distribution pattern in the Federal Capital Territory (FCT) Abuja, is dominated by Ferric Luvisols, which cover the largest proportion of land with an area

of 4969.86 km², representing 62.28% of the territory. These soils are typically fertile and suitable for agriculture, indicating that a significant portion of Abuja is favourable for farming and plant growth (see Fig. 10 and Table 9).

Table 9. Land Use/Land Cover Classification in FCT Abuja.

Sn	Soil Type	Area (km ²)	Coverage (%)
1	Lithosols	2844.22	35.64
2	Ferric Luvisols	4969.86	62.28
3	Plinthic Luvisols	140.86	1.77
4	Dystic Nitisols	24.80	0.31

The second most extensive soil type is Lithosols, covering 2844.22 km² (35.64%) of the area. Lithosols are typically shallow and stony soils that often form in areas with steep slopes or rocky terrain. While they provide some agricultural potential, their shallow nature and susceptibility to erosion may limit intensive farming and groundwater infiltration.

Other soil types occupy much smaller portions of the FCT. Plinthic Luvisols cover 140.86 km² (1.77%), often associated with iron-rich layers that harden upon exposure, which can restrict root penetration and water infiltration. Simi-

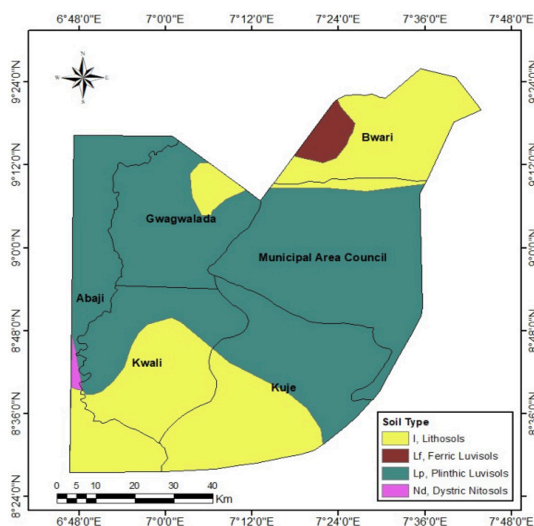


Fig. 10. Soil type map of FCT Abuja.

larly, Dystric Nitisols, covering just 24.80 km² (0.31%), represent the least dominant soil type in the region. Despite their minimal coverage, these soils are generally well-structured and support agricultural productivity where present.

Luvisols are texturally differentiated soils characterized by a clay-enriched sub-soil (argic horizon), high base saturation, and loamy to clayey textures that support agriculture, although management is required to sustain productivity. Ferric Luvisols, enriched with iron oxides, display reddish to yellowish subsoils and are well-drained but prone to slight acidity and occasional waterlogging. Plinthic Luvisols, characterized by hardened plinthic horizons, restrict root growth and water infiltration despite their nutrient-rich nature, making them challenging for farming without proper management. Dystric Nitisols, common in humid tropics, are acidic, nutrient-deficient, and leached but support crops like cassava, maize, and legumes with appropriate soil amendments (WRB, 2014).

In general, the soil composition of the FCT Abuja reveals a landscape largely dominated by Ferric Luvisols and Lithosols, which together account for nearly 98% of the total land area.

This dominance underscores their significance in shaping agricultural practices, land management, and groundwater recharge potential within the region, while the minor soil groups play localized roles in land use suitability.

7. Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) aimed to assess groundwater potential in the Federal Capital Territory (FCT) based on eight different criteria. These criteria include Rainfall, Geology, Slope, Drainage Density, Land Use/Land Cover, Lineament Density, Soil Type, and the Topographic Wetness Index (TWI). Each criterion plays a role in influencing the likelihood of groundwater potential, and their relative importance is quantified using the AHP method.

The weight assignment process indi-

cates that each criterion has been assigned a specific weight, reflecting its contribution to groundwater potential in the study area. The weights range from 3.8% to 34.2%, with Rainfall (34.2%), Geology (23.7%), and Slope (13.7%) being the most influential factors.

The relative importance of groundwater conditioning factors was determined using the Analytical Hierarchy Process (AHP) proposed by Saaty (1980). Pairwise comparisons were conducted using the 1–9 Saaty scale based on expert hydrogeological judgment and literature from similar geological environments. A total of 11 experts participated in the evaluation, and the aggregated comparison matrix was derived using the geometric mean method. Factor weights were calculated from the principal eigenvector of the normalized matrix. The consistency ratio (CR) was computed to evaluate judgment reliability, and a CR value of 0.0451 (<0.10) confirmed acceptable consistency. This procedure ensures that the weighting scheme is methodologically robust and reproducible.

The analysis also provides an eigenvalue (λ) of 8.449, which is very close to the number of criteria (8). This indicates that the pairwise comparisons made between the criteria in the AHP process are consistent. A consistency ratio (CR) of 4.6%, which is well below the acceptable threshold of 10%, confirms that the comparisons are reliable.

7.1 Assigned and normalized weights of different features

The methodology for assigning and normalizing weights in this study was derived from a diverse selection of international expert studies addressing hydrological issues globally. The approach employed Saaty's Analytical Hierarchy Process (AHP) technique (Saaty, 2008), to de-

termine the weights assigned to various thematic layers and their associated features used in groundwater potential zone (GWPZ) mapping. The calculation of the consistency ratio was carried out through the following steps:

Calculation of principal eigenvalue (λ) using the eigenvector method.

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

where n is the number of criteria or factors, CI is consistency Index.

7.2 Computation of the consistency ratio (CR)

$$CR = \frac{CI}{RCI},$$

where RCI refers to a random consistency index (see Table 2).

Eight thematic layers were analysed: Rainfall, Geology, Slope, Drainage Density, Land Use/Land Cover, Lineament Density, Topographic Wetness Index, and Soil Type. The vector layers were converted into raster formats to enable integration with other raster-based thematic layers during the GIS modelling process. A re-sampling procedure was applied to ensure all thematic layers had uniform resolution.

Each theme was assigned a specific weight based on its relative contribution and influence on groundwater reserves.

Each of the values in column Sum A1 (Table 11) is calculated using the values in the first row of Table 10, which are multiplied from left to right as demonstrated below; $= (1 \times 3 \times 3 \times 5 \times 5 \times 5 \times 5 \times 5)^{1/8} = 3.599$. The weights in A2 are each calculated by dividing the value in the (sum A1) column by the total in the same column (10.815)

From Table 11 above, $\lambda - max = 67.561/8 = 8.445$, $n = 8$ and $RCI = 1.41$ (From Table 2)

Consistency Index

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{8.445 - 8}{8 - 1} = \frac{0.455}{7} = 0.0636$$

7.3 Consistency ratio

$$CR = \frac{CI}{RCI} = \frac{0.0636}{1.41} = 0.0451$$

Since 0.0451 is less than 0.1, it indicates a reasonable level of consistency in the pairwise comparisons.

Therefore, the weights of 0.3327, 0.2372, 0.1383, 0.0946, 0.0709, 0.0494, 0.0384 and 0.0384 (corresponding to 33.27%, 23.72%, 13.83%, 9.46%, 7.09%, 4.94%, 3.84% and 3.84%, respectively) can be assigned to Slope, Lineament Density, Drainage Density, Land Use/Land Cover, Soil Type, Geology, Rainfall and the Topographic Wetness Index (TWI), respectively.

8. Groundwater Potential Zones Calculation

To ensure uniformity and ease of computation, all parameters were resampled to a 30m spatial resolution. The parameters were then assigned weights using the Analytical Hierarchy Process (AHP), reflecting their relative importance to groundwater potential in the study area. Each parameter was classified and rated based on its contribution to groundwater potential, with higher values indicating greater significance (as shown in Tables 4.3a-4.3b). Finally, a weighted overlay analysis was performed using the Weighted Overlay tool in ArcMap 10.7.1, integrating all the parameters to generate the groundwater potential map for the study area.

The Analytical Hierarchy Process (AHP), integrated with Geographic Infor-

mation Systems (GIS) and Remote Sensing (RS), provides a systematic approach to mapping groundwater potential by evaluating multiple factors that influence groundwater recharge. For the Federal Capital Territory (FCT) of Abuja, a groundwater potential map (Fig. 11) was developed using an AHP-based Multicriteria Decision-Making (MCDM) approach. Eight factors, including rainfall, geology, slope, lineament density, land use/land cover (LULC), drainage density, soil type, and topographic wetness index (TWI), were analysed through thematic maps and weighted based on their influence. Weighted index overlay analysis combined these factors, identifying areas with high cumulative values as zones with good groundwater potential.

The study classified the region into three groundwater potential zones (see Fig. 11 and Table 12): Low (9.15%, in the west and southwest), Medium (82.29%), and High (8.56%, in the north and northeast).

The application of the Analytical Hierarchy Process (AHP) in groundwater potential mapping faces challenges related to subjectivity, data quality, and system complexity.

Assigning weights to factors influencing groundwater recharge involves subjective judgments, which, despite a consistency ratio (CR) of 0.012 deemed acceptable in the study, can still impact results. The approach also relies heavily on high-quality and precise data; however, limitations in the resolution or accuracy of satellite and field data can affect the reliability of outcomes.

Additionally, while AHP simplifies complex hydrogeological systems into thematic layers, such as geology, geomorphology, slope, lineament density, drainage

Table 10. Pairwise comparison matrix of 8 criteria for the AHP process.

MATRIX A1										
		RF	GEOL	SL	DD	LU	LD	TWI	ST	NPE
		1	2	3	4	5	6	7	8	
RF	1	1.0000	3.0000	3.0000	5.0000	5.0000	5.0000	5.0000	5.0000	34.2%
GEOL	2	0.3333	1.0000	3.0000	3.0000	5.0000	5.0000	5.0000	5.0000	23.7%
SL	3	0.3333	0.3333	1.0000	1.0000	3.0000	3.0000	5.0000	5.0000	13.7%
DD	4	0.2000	0.3333	1.0000	1.0000	1.0000	2.0000	3.0000	3.0000	9.1%
LU	5	0.2000	0.2000	0.3333	1.0000	1.0000	1.0000	3.0000	3.0000	7.1%
LD	6	0.2000	0.2000	0.3333	0.5000	1.0000	1.0000	1.0000	1.0000	4.7%
TWI	7	0.2000	0.2000	0.2000	0.3333	0.3333	1.0000	1.0000	1.0000	3.8%
ST	8	0.2000	0.2000	0.2000	0.3333	0.3333	1.0000	1.0000	1.0000	3.8%

Note: RF = Rainfall, GEOL = Geology, SL = Slope, DD = Drainage Density, LU = Land Use/Land Cover, LD = Lineament Density, TWI = Topographic Wetness Index and ST = Soil Type. NPE = Normalized Principal Eigenvector.

Table 11. Determining The λ -max, consistency index and consistency ratio.

Sn	Sum A1	Matrix A2 Weight	Matrix A3 A1×A2	Matrix A4 A3/A2	Consistency Index (CI)	Consistency Ratio (CR) CI/RCI
1	3.599	0.3327	2.918	8.770	0.110	0.078
2	2.565	0.2372	2.033	8.570	0.081	0.058
3	1.495	0.1383	1.168	8.449	0.064	0.045
4	1.023	0.0946	0.779	8.233	0.033	0.024
5	0.767	0.0709	0.606	8.537	0.077	0.054
6	0.535	0.0494	0.405	8.185	0.026	0.019
7	0.416	0.0384	0.323	8.409	0.058	0.041
8	0.416	0.0384	0.323	8.409	0.058	0.041
	10.815	1.000	8.554	67.561	0.509	0.361

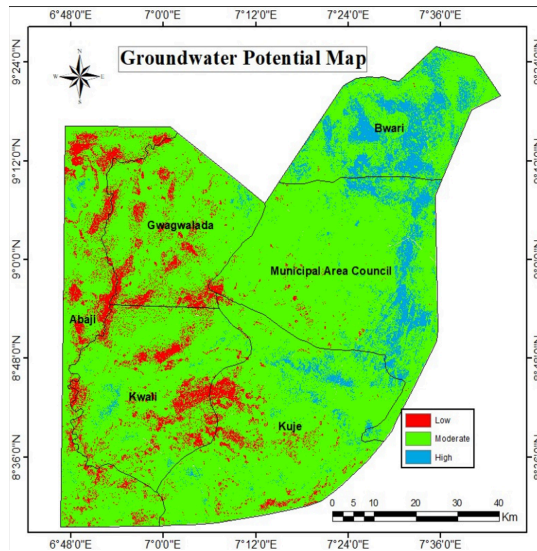


Fig. 11. Groundwater potential zone of FCT Abuja.

density, and land use/land cover, it may overlook critical interactions among these factors.

These challenges highlight the neces-

sity for meticulous validation to improve the accuracy and reliability of AHP-based groundwater potential mapping (Sadek et al., 2021).

Table 12. Influencing factors, potentials for groundwater, rate and normalized weights.

Sn	Influencing Factors	Category (Classes)	Potentiality for groundwater storage	Rating (r)	Normalized Weight
1	Rainfall	1278 – 1353	Very Good	5	34.2
		1220 – 1278	Good	4	
		1153 – 1220	Moderate	3	
		1087 – 1153	Poor	2	
		1013 – 1087	Very Poor	1	
2	Geological Map	Sandstone	Very Good	5	23.7
		Medium-coarse grained biotite gneiss	Good	4	
		Migmatite Gneiss	Good	4	
		Migmatite	Good	4	
		Granite porphyry	Moderate	3	
		Quartzite	Moderate	3	
		Biotite Granodiorite	Moderate	3	
		Granite gneiss	Moderate	3	
		Coarse porphyritic biotite granite	Moderate	3	
		Porphyroblast Gneiss	Moderate	3	
		Biotite Gneiss	Moderate	3	
		Amphibolite Schist	Poor	2	
		Medium-grained biotite granite	Poor	2	
		Undifferentiated older granite	Poor	2	
		Undifferentiated Schist	Poor	2	
		Quartz muscovite Schist	Poor	2	
3	Slope	0 – 3.38	Very Good	5	13.7
		3.38 – 7.32	Good	4	
		7.32 – 13.52	Moderate	3	
		13.52 – 21.70	Poor	2	
		21.70 – 71.86	Very Poor	1	
4	Drainage Density	0.09 – 0.74	Very Good	5	9.1
		0.74 – 0.95	Good	4	
		0.95 – 1.14	Moderate	3	
		1.14 – 1.35	Poor	2	
		1.35 – 2.10	Very Poor	1	
5	LULC	Bare ground	Poor	2	7.1
		Rangeland	Moderate	3	
		Crops	Moderate	3	
		Trees	Moderate	3	
		Flooded Vegetation	Good	4	
		Water	Very Good	5	
6	Lineament Density	0 – 0.3	Very Poor	1	4.7
		0.3 – 0.61	Poor	2	
		0.61 – 0.9	Moderate	3	
		0.9 – 1.17	Good	4	
		1.17 – 1.64	Very Good	5	
7	Topographic Wetness index	2.35 – 6.53	Very Poor	1	3.8
		6.53 – 8.07	Poor	2	
		8.07 – 10.34	Moderate	3	
		10.34 – 13.6	Good	4	
		13.6 – 25.49	Very Good	5	
8	Soil Type	Lithosols	Very Poor	1	3.8
		Plinthic Luvisols	Poor	2	
		Ferric Luvisols	Moderate	3	
		Dystic Nitosols	Good	4	

9. Conclusion

This research demonstrates that the groundwater potential in the Federal Capital Territory (FCT), Abuja, is influenced

by a combination of topographic, geological, hydrological, climatic, and land-use factors. The results reveal that slope and drainage density influence recharge

in opposite ways: gentle slopes and low drainage densities encourage infiltration and recharge, while steep slopes and dense drainage networks increase runoff and limit infiltration. Lineament density also plays a key role, with moderately to highly fractured zones supporting recharge, storage, and aquifer connectivity—although highly fractured areas may also increase the risk of contamination. The Topographic Wetness Index (TWI) further demonstrates how terrain features guide water accumulation and recharge.

Rainfall distribution introduces clear spatial differences in recharge potential, with the wetter northeastern part of the FCT showing stronger recharge prospects compared to the drier southwest, where water management needs to be more strategic. Land use and cover also play a role: vegetation and farmlands allow for better infiltration, while urbanized areas reduce recharge due to impervious surfaces. Similarly, geology and soils add complexity: sedimentary rocks and weathered or fractured basement formations favour aquifer development, whereas shallow lithosols and compact soil layers limit infiltration.

The Analytical Hierarchy Process (AHP) identified rainfall, geology, and slope as the most important factors shaping groundwater potential, with the model's consistency ratio confirming the reliability of this weighting. By combining all these factors through geospatial modelling, the study provides a detailed and reliable map of groundwater potential zones across the FCT. These findings highlight the importance of a multi-criteria, GIS-based approach for sustainable water resource planning. The delineated potential zones serve as a practical guide for groundwater exploration, policy-making, and long-term management, especially in light of growing wa-

ter demand and climate variability.

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