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Groundwater Mapping Through Integration of Resistivity Survey, Remote Sensing, Geographic Information Systems and AHP Techniques in Bwari Area Council, FCT Abuja, Nigeria

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Abstract: This study presents an integrated, multi-criteria approach to delineating groundwater potential zones in the Bwari Area Council, Federal Capital Territory, Abuja, Nigeria, employing a combination of Vertical Electrical Sounding (VES) resistivity surveys, remote sensing, Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP). Using satellite imagery, DEMs, digitized maps, and field observations, thematic layers—rainfall, geology, slope, drainage density, land use/land cover, lineament density, soil type, and topographic wetness index—were generated and validated through GIS and remote sensing techniques. Weights were assigned to each factor using AHP, prioritizing parameters based on their hydrogeological significance. Thematic layers were integrated via weighted overlay analysis in ArcGIS to produce a spatially explicit groundwater potential map. Subsurface information was acquired through VES at 23 locations, with resistivity data interpreted to characterize aquifer properties (resistivity, thickness, depth, and overburden). The results reveal a dual aquifer system, comprising a shallow weathered zone and a deeper fractured basement aquifer, with groundwater occurrence predominantly controlled by secondary porosity features. Moderate-to-high groundwater potential zones were found to constitute over 85% of the study area, with high-potential regions associated with thick, weathered, and fractured lithologies, low drainage density, gentle slopes, and favourable land cover. Comparative analysis between the integrated thematic (RS/GIS/AHP) and aquifer-parameter (VES) models yielded a high correspondence (78.7%), confirming the reliability of the multi-criteria method and underscoring the importance of combining surface and subsurface data. The study advances methodological frameworks for groundwater assessment in crystalline basement terrains and provides a robust scientific basis for sustainable borehole siting, groundwater resource development, and land-use planning. The approach is replicable in similar hydrogeological settings, offering important implications for water resource management in data-scarce, complex geological environments.

Keywords: *Groundwater Potential Mapping; Geographic Information Systems (GIS); Vertical Electrical Sounding (VES); Analytical Hierarchy Process (AHP); Basement Complex Aquifer.*

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I. INTRODUCTION

Vertical Electrical Sounding (VES) is an essential geophysical technique for characterizing the lithology of subsurface environments. This approach involves introducing an electrical current into the ground and recording the resulting potential difference, enabling the determination of subsurface resistivity distributions. VES is widely applied in two-dimensional (2D) resistivity surveys to delineate geological structures and identify potential aquifer zones by analyzing resistivity variations among subsurface layers [1]; [2]. Geoelectrical resistivity investigations employing deep VES stations have demonstrated significant utility in the exploration of freshwater aquifers. These surveys yield quantitative insights into the electrical resistivities of subsurface materials, providing crucial information about geological stratification, structural features, and groundwater occurrence [3]. This methodology is particularly valuable for

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hydrogeological studies in hard-rock terrains, where groundwater occurrence is governed by secondary porosity, permeability in weathered zones, and structural discontinuities such as faults and fractures [4].

The integration of resistivity surveys, remote sensing, Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP) has proven highly effective for groundwater exploration in basement complex regions [5]. This multidisciplinary methodology enables the precise delineation of subsurface features that are critical to groundwater movement and storage [4] and enhances the reliability of potential groundwater zone identification [6]. By synthesizing surface information obtained from remote sensing and GIS with subsurface resistivity data, and applying systematic weighting through the AHP, researchers can achieve comprehensive hydrogeological assessments [7]. The AHP provides a quantitative framework for evaluating and prioritizing factors such as lithology, fracture density, degree of weathering, and hydrological parameters, thereby improving the precision of groundwater potential mapping [8]. This integrated approach surpasses conventional geophysical surveys by incorporating multiple variables that influence groundwater occurrence, resulting in a more holistic understanding of aquifer systems [5]. It is widely adopted for the preparation, integration, and analysis of thematic layers in groundwater zonation studies worldwide [9].

The integrated approach fosters a comprehensive understanding of subsurface hydrogeological conditions, which is essential for the sustainable management of water resources in basement complex terrains [6]. Importantly, this methodology has demonstrated improved accuracy in delineating groundwater potential zones, optimized well placement through the identification of lineaments and fracture systems, and enhanced operational efficiency by minimizing the need for extensive manual field surveys [10]; [4]; [11]. In countries such as Nigeria, where water demand is rapidly increasing, the adoption of these advanced techniques supports the fulfillment of domestic, agricultural, and industrial water requirements while promoting the efficient utilization of resources [12]. The present study evaluates and maps groundwater potential zones within the Bwari Area Council of the Federal Capital Territory (FCT), Abuja, Nigeria, by integrating resistivity surveys, remote sensing, GIS, and the Analytical Hierarchy Process (AHP). This integration facilitated the effective identification of groundwater zones through the analysis of thematic layers, including geology, geomorphology, rainfall, and lineament structures [7]. The subsequent section provides a detailed description of the study area.

II. THE STUDY AREA

The Bwari Area Council (Figure 1) is predominantly underlain by Precambrian Basement Complex rocks. These rocks include granites, pegmatites, schists, and gneisses. They form the rugged hills and undulating plains characteristic of north-central Nigeria [13]. These rocks are mainly granite, granite-gneiss, and gneiss that weather into reddish sandy clay or clay with mica. They are often capped by laterite. Although they are typically poor aquifers (rock formations that can hold and transmit groundwater), weathering and fracturing enhance groundwater storage and flow [14]; [15]. Dominant lithologies (types of rock units) documented by previous researchers include granites, gneisses, mica schists, hornblende- and feldspathic schists, and migmatites. All of these display significant fracturing and exhibit two main fracture trends: NE–SW and NW–SE.

Notably, these structural features control river flow and drainage. They also shape groundwater movement by creating both barriers and conduits [16]; [17]. VES (Vertical Electrical Sounding, a method used to study subsurface layers) confirms extensive weathering and a high fracture index. Both are favourable for groundwater occurrence. The complex geological setting is marked by metamorphic and igneous formations. These formations influence both the distribution of minerals and the potential for groundwater. The crystalline rocks often serve as the primary targets for geophysical investigations [4]. They frequently display two main fracture orientations, NE-SW and NW-SE, which parallel regional schist belts and the Cretaceous Bida Basin [5].

The area has a tropical savanna climate and a population of approximately 176,514, primarily comprising the Gbagyi and Hausa [18]. Abuja's climate is described as tropical wet and dry, with an annual average temperature range of 25.8°C to 30.2°C [19].

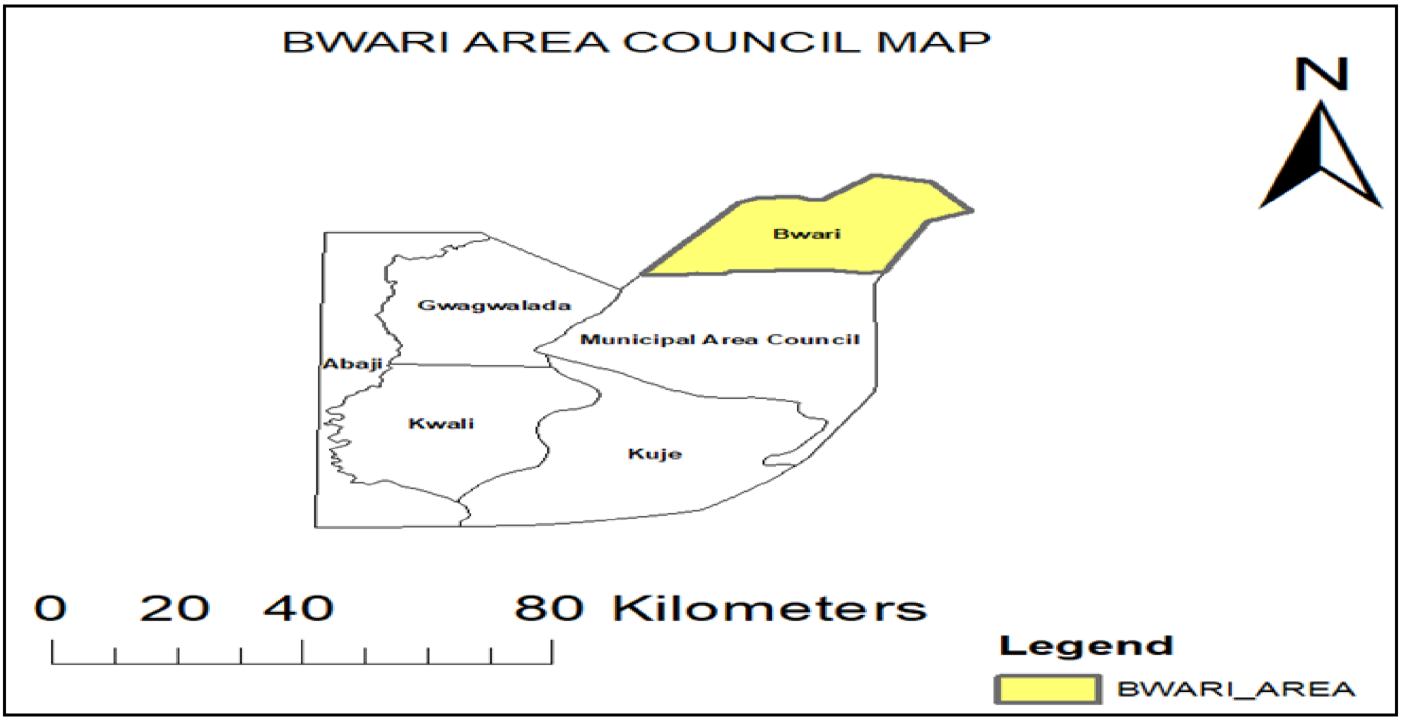

Fig 1 Map of Bwari Area Council

III. METHODOLOGY

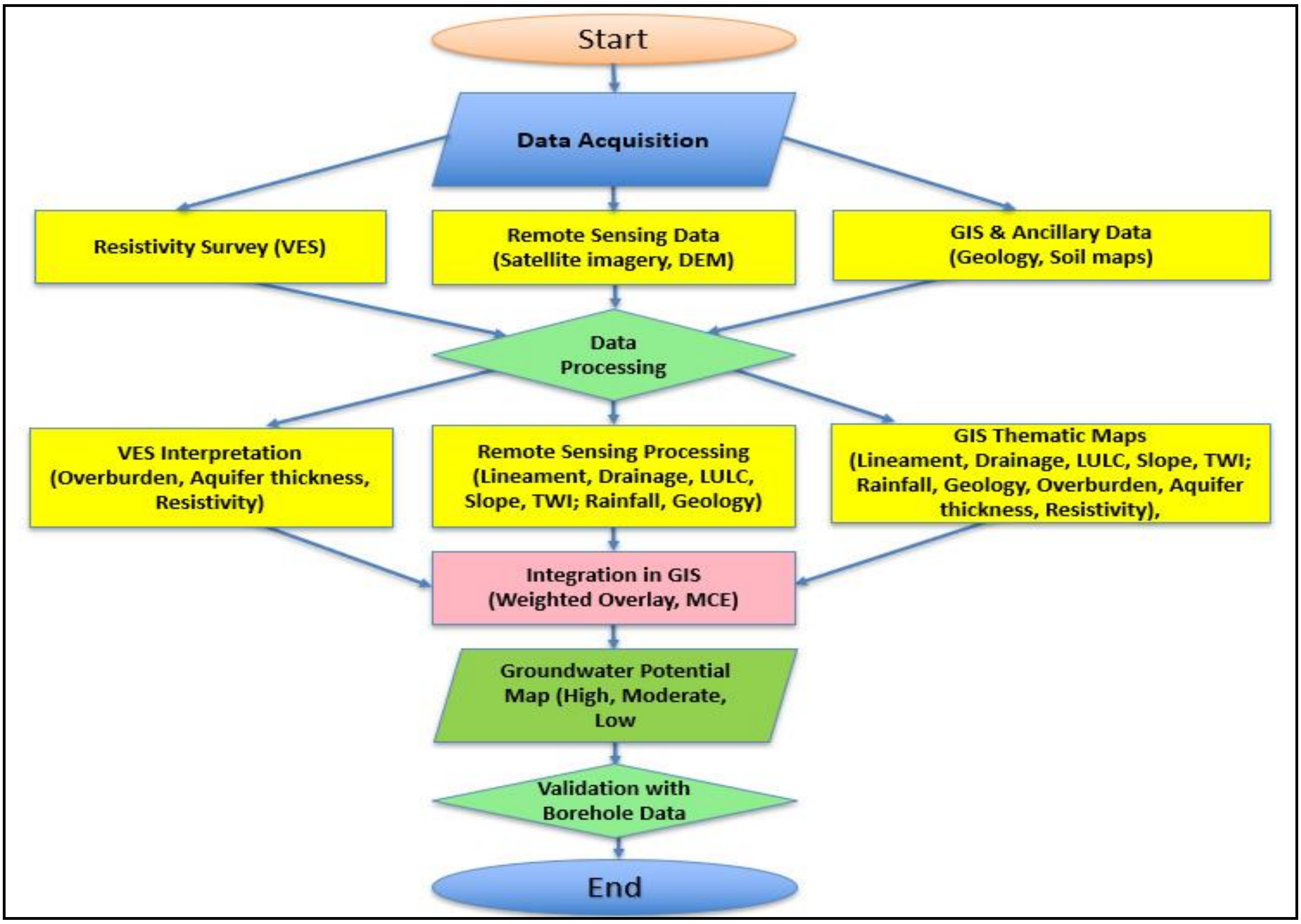

Fig 2 Flowchart of the Methodology

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➢ *Derivation of the Thematic Layers*

The study generated thematic layers using satellite imagery, DEMs, digitized maps, and field observations to identify groundwater potential zones. These layers are rainfall, geology, slope, drainage density, land use/land cover, lineament density, topographic wetness index, and soil, which were validated through Remote Sensing and GIS techniques. They were then weighted and analyzed in ArcGIS 10.7.1 to delineate groundwater potential zones.

➢ *The Analytic Hierarchy Process (AHP)*

The Analytic Hierarchy Process (AHP) commences with the explicit articulation of the problem and principal objective, such as the evaluation or prioritization of groundwater potential zones. The issue is subsequently organized into a hierarchical structure, positioning the overarching goal at the apex, followed by pertinent criteria, any sub-criteria, and alternatives at the base. Each criterion is subjected to pairwise comparison utilizing Saaty's 1–9 scale (Table 1) to ascertain their relative importance. The resulting comparison matrix is normalized to derive the weight of each criterion. Logical consistency is evaluated using the consistency ratio (CR), where a value less than 0.1 is considered acceptable. Weighted scores are obtained by multiplying the normalized weights by the respective values of sub-criteria or alternatives. Alternatives are then ranked according to their composite scores to determine the most appropriate or influential factors.

The method begins by identifying key decision-making factors and arranging them in a square pairwise comparison matrix, where each row and column represents a factor. Their comparison values are then organized to enable systematic evaluation. This structure allows for direct comparison among all factors and supports the calculation of the priority vector used for weighting decisions.

➢ *Computation of Normalized Weights*

Table 1 Saaty's 1–9 Scale of Relative Importance [20]

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 'n' Values [20]

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

RI = RCI = Random Consistency Index

- *Consistency Index CI*

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

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.

- *Consistency Ratio (CR)*

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

$$CR = \frac{CI}{RI} \quad (2)$$

where RI is the Ratio Index; The value of RI for different n values is given in Table 2.

For n = 8, RI = 1.41

➢ *Delineation of the Groundwater Potential Zones*

To produce the groundwater potential zone map for the study area, the seven thematic layers are synthesized through the application of the weighted overlay analysis function in the ArcGIS platform. This process is executed in accordance with the following equation:

$$GWPI = \sum[(RFw \times RFwi) + (Geolw \times Geolwi) + +(SLw \times SLwi) + (DDw \times DDwi) + (LDw \times LDwi) + (STw \times STwi) + (LUw \times LUwi) + (TWIw \times TWIwi)] \quad (3)$$

In this context, GWPI denotes the groundwater potential index; RF represents Rainfall; Geol indicates Geology; SL signifies Slope; DD denotes Drainage Density; LD corresponds to Lineament Density; ST refers to Soil Type; LU stands for Land Use/Land Cover; and TWI represents the Topographic Wetness Index. The subscripts "w" and "wi" signify the normalized weights assigned to each thematic layer and individual feature, respectively. The generated groundwater potential zone map will be classified

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into categories indicating low, moderate, high, and very high potential.

IV. RESULTS AND DISCUSSIONS

➤ *Slope and Groundwater Potential*

The terrain slope was assessed using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) within the ArcGIS 10.7.1 environment. The Slope function was employed to derive slope values, which are expressed in degrees. Slope, which quantifies the steepness or inclination of the land surface, was calculated by evaluating the maximum rate of elevation change between each pixel and its neighbouring pixels. The formula utilized for slope calculation is provided below:

$$\text{Slope} = \arctan\left(\frac{\Delta Z}{D}\right) \tag{4}$$

Here, ΔZ denotes the variation in elevation, while D indicates the horizontal distance separating two points. The computation yields a raster dataset, with each cell value corresponding to the calculated slope at that specific location, thereby facilitating a comprehensive analysis of terrain steepness throughout the study region. This methodology is consistent with the guidelines presented by [21].

Slope, as a geomorphological factor, influences groundwater recharge by affecting infiltration. Gentle slopes promote infiltration and recharge, while steep slopes increase runoff and limit infiltration, indicating variations in groundwater potential [22].

The slope in the Bwari area council, 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 characterized as flat or gently sloping, which promotes 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, such as 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. The slope regulates subsurface water movement, influencing groundwater replenishment by affecting both surface runoff and infiltration [23].

Gentle slopes generally facilitate greater infiltration and longer surface water residence times, thereby increasing groundwater recharge potential. In contrast, steep slopes lead to rapid runoff and reduced infiltration [24]; [12].

Figure 3 shows the Slope Map of Bwari Area Council, classified into five categories: (0 - 3.38); (3.38 - 7.32); (7.32 - 13.52); (13.52 - 21.70); and (21.70 - 71.86) degrees.

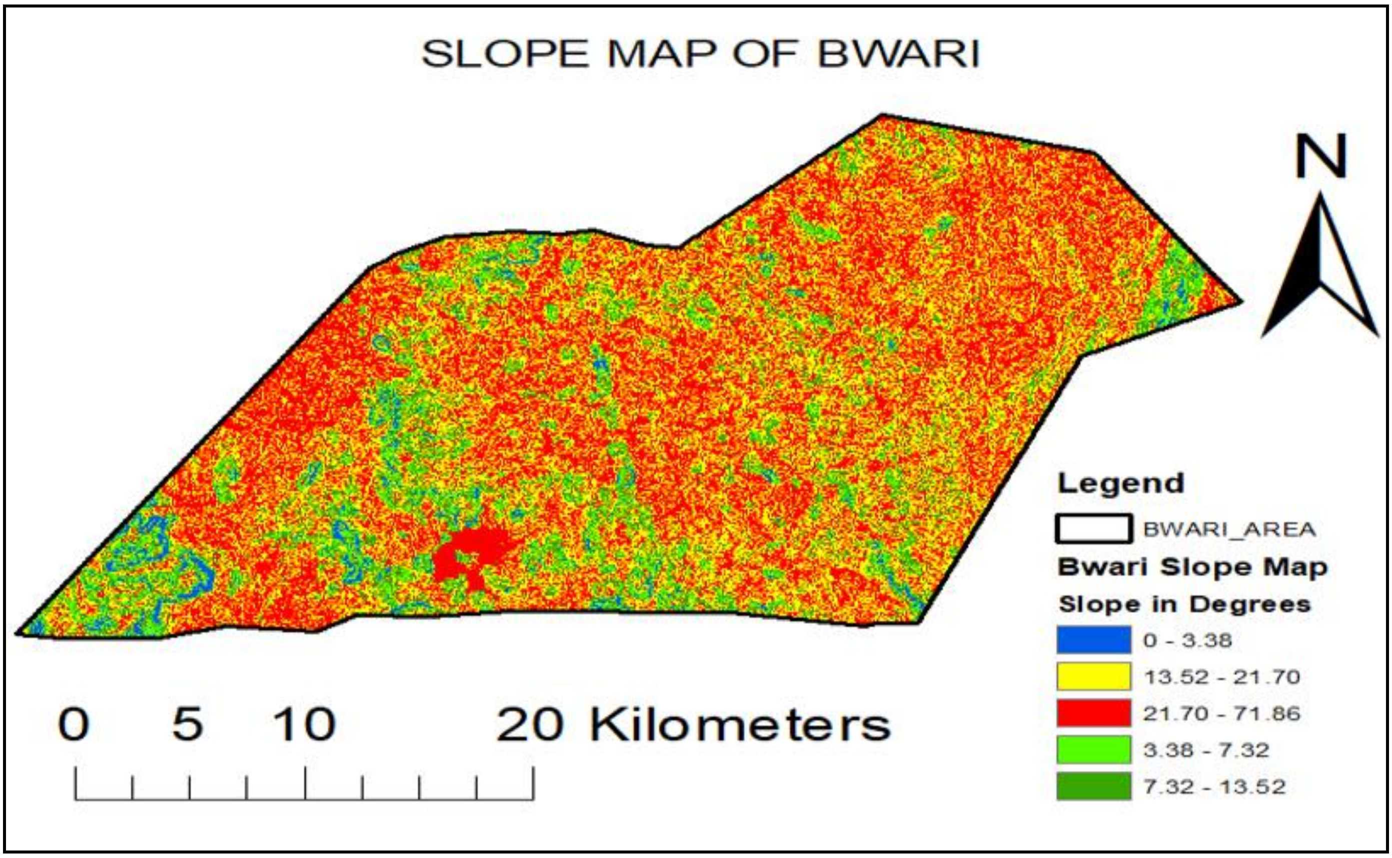

Fig 3 Slope Map of Bwari Area Council

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Table 3 indicates that the Bwari area council watershed is predominantly characterized by steep and very steep slopes. The very steep slope category (21.70–71.86°) encompasses 397.32 km², representing 43.58% of the total area. The steep slope category (13.52–21.70°) covers 349.51 km², accounting for 38.34%. Collectively, these two categories constitute 81.92% of the watershed, reflecting a high potential for surface runoff and limited infiltration capacity.

Table 3 Slope Classification in Bwari Area Council

Sn	Slope (°)	Area (km^2)	Percentage (%)	Classes
1	0 - 3.38	16.67	1.83	Low
2	3.38 - 7.32	44.41	4.87	Moderate
3	7.32 - 13.52	103.82	11.39	Transitional
4	13.52 - 21.70	349.51	38.34	Steep
5	21.70 - 71.86	397.32	43.58	Very Steep

As shown in Table 3 and Figure 3, the Bwari Area Council was divided into five slope classes using ArcMap 10.7.1 analytical tools: low (0–3.38°), moderate (3.38–7.32°), transitional (7.32–13.52°), steep (13.52–21.70°), and very steep (21.70–71.86°). The results highlight the predominance of steep and very steep slopes, indicating a rugged terrain with sharp elevation gradients. These topographic features shape hydrological processes, surface stability, and land-use suitability.

The low slope class (0–3.38°) occupies about 182.32 km² (2.29%) and represents the gentlest terrain in the study area. These zones are found in valley bottoms and low-lying plains. Surface runoff is minimal here. Infiltration rates are highest. As a result, these areas play a crucial role in groundwater recharge, soil moisture retention, and agricultural productivity. They are ideal for settlement expansion and infrastructural development. The moderate slope class (3.38–7.32°) covers about 451.52 km² (5.67%). It allows better infiltration than steeper zones. While moderate slopes allow partial runoff, infiltration is still sufficient to support aquifer recharge and sustainable land use.

The transitional slope class (7.32–13.52°) covers approximately 850.51 km² (10.67%). These zones represent intermediate relief terrains. Both runoff and infiltration occur in balance. Recharge potential is moderate due to partial infiltration. These areas are hydrologically important because they serve as buffer zones between high runoff uplands and low-lying recharge plains. Their soil and vegetation conditions affect how well they retain water and reduce surface erosion.

The Steep (13.52–21.70°) and very steep (21.70–71.86°) slope classes dominate the landscape. They cover most of the Bwari Area Council. These terrains experience rapid surface runoff and limited infiltration. This increases the potential for erosion and reduces groundwater recharge. The steeper gradients make water percolation into the subsurface more difficult. These zones are less favourable for groundwater development. The predominance of these slopes means that much of Bwari is hydrologically unfavourable for deep infiltration. However, these areas are crucial for surface water flow and the formation of drainage.

The slope distribution pattern shows that gentle to moderately sloping areas give the most favourable conditions for groundwater recharge. Steep and very steep slopes mainly contribute to surface runoff and erosion. This pattern reflects the inverse relationship between slope gradient and groundwater potential [25]. Flatter surfaces are assigned higher groundwater potential ratings (“5”). The steepest terrains are rated lowest (“1”). The dominance of high-relief areas underscores the importance of soil conservation, erosion control, and adaptive land management practices. The limited lowland zones are key targets for groundwater exploration, sustainable agriculture, and settlement planning in the Bwari Area Council.

➤ *Drainage Density and Groundwater Potential*

Drainage density was determined using the SRTM Digital Elevation Model (DEM) within the ArcGIS environment. Initially, the DEM was processed with the Fill tool to eliminate artificial depressions. The Flow Direction tool was then used to establish the direction of surface water movement. Next, the Flow Accumulation tool identified zones of significant water accumulation. A threshold value (typically 500 or greater) was set to delineate the drainage network. This network was then transformed into a vector stream network using the Raster to Polyline tool. Finally, the Kernel Density tool was used to compute drainage density. Drainage density is defined as the total stream length per unit area according to the following formula:

$$Dd = \frac{L}{A} \quad (5)$$

Here, 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 [26].

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. These areas have permeable soils, gentle slopes, and high groundwater recharge potential. They are ideal for agriculture and water retention. A low drainage density (0.74–0.95) indicates a balance between runoff and infiltration. This balance supports sustainable agricultural and forest practices. Moderate drainage density (0.95–1.14) suggests a mix of runoff and infiltration. Mixed land use in these areas needs erosion control. High drainage density (1.14–1.35) shows poor drainage with limited infiltration. Erosion and flood

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risks increase here. A very high drainage density (1.35–2.10) reflects runoff dominance in impermeable or steep terrain. Soil conservation and flood mitigation measures are necessary. Effective management depends on understanding local geology, climate, and vegetation to address these conditions.

A negative relationship exists between drainage density and groundwater recharge in a region. High drainage densities reduce infiltration rates [27]. This inverse relationship means that areas with lower drainage density are more suitable for groundwater accumulation. These areas become prime candidates for groundwater potential zones; Regions with elevated drainage densities exhibit lower groundwater potential due to increased runoff and reduced percolation into the subsurface [5]; [24].

This phenomenon is due to the faster removal of surface water. Quick removal shortens the time available for water to sink into porous media. As a result, groundwater replenishment is limited [5].

Low drainage density favours 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 [28].

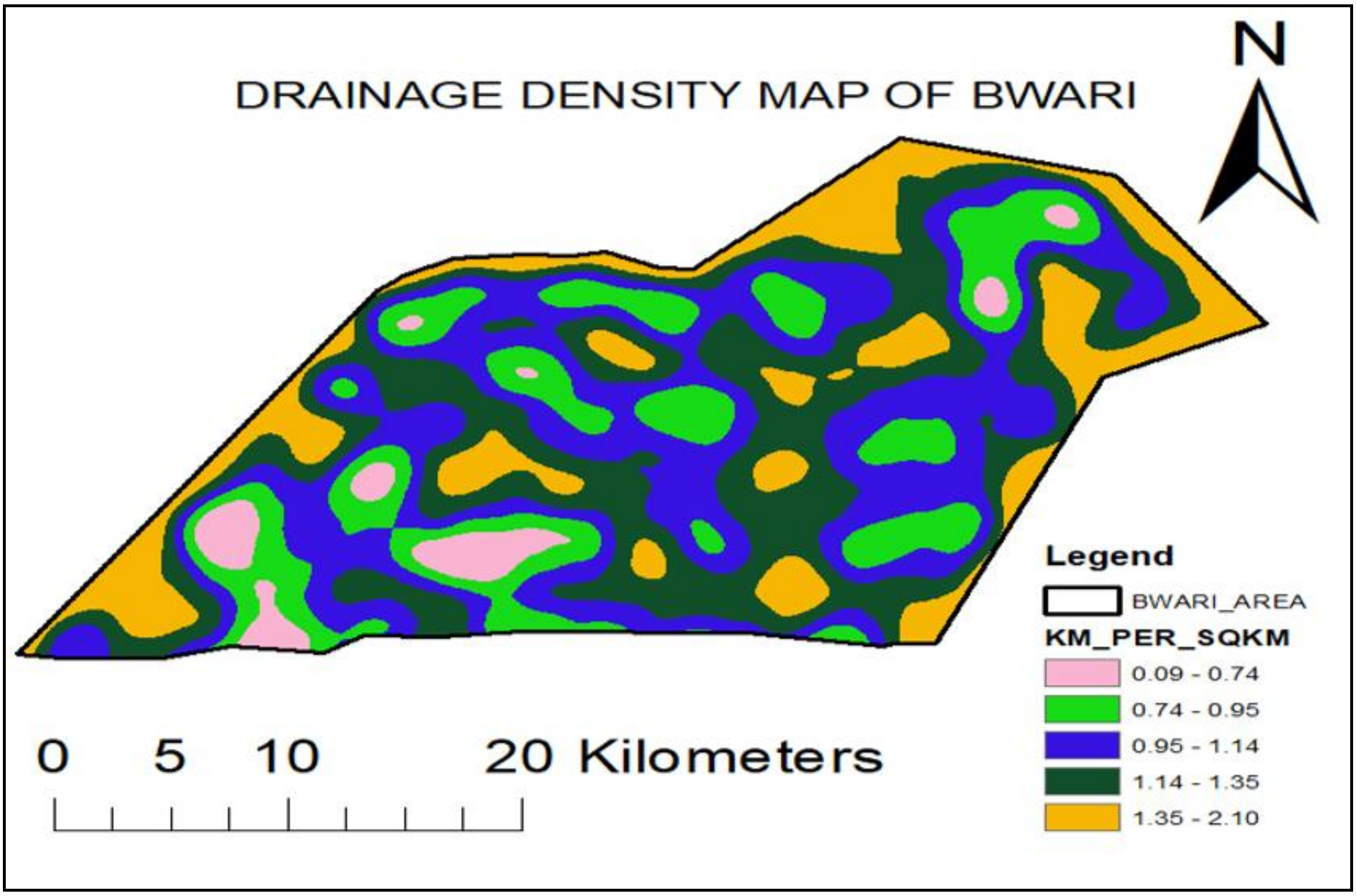

Fig 4 Drainage Density Map of Bwari

Figure 4 and Table 4 illustrate the spatial distribution of drainage density within the Bwari Area Council, classified into five distinct categories ranging from "very high" to "very low." The moderate (0.95–1.14 km/km²) and low (1.14–1.35 km/km²) drainage density classes collectively account for approximately 60.43% of the total area. The predominance of these categories indicates a balanced interplay between surface runoff and infiltration, thereby facilitating moderate groundwater recharge and mitigating excessive erosion.

Table 4 Drainage Density Classification in Bwari

Sn	Drainage Density (km/km^2)	Area (km^2)	Coverage (%)	Classes
1	0.09 – 0.74	36.52	3.99	Very High
2	0.74 – 0.95	157.74	17.25	High
3	0.95 – 1.14	278.53	30.46	Moderate
4	1.14 – 1.35	274.00	29.97	Low
5	1.35 – 2.10	167.59	18.33	Very Low

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The very low drainage density group (1.35–2.10 km/km²) comprises 18.33% of the area and is associated with porous, cracked ground that facilitates water seepage (Table 4). In contrast, the high (0.74–0.95 km/km²) and very high (0.09–0.74 km/km²) groups, which together comprise 21.24%, exhibit traits that encourage more surface water flow, erosion, and flooding, as well as less groundwater recharge.

Drainage density in the Bwari Area Council exhibits a mix of water patterns shaped by the steepness of the land, the type of rocks present, and the ease with which water can move through the soil. Most areas have moderate to low drainage, which helps recharge groundwater, but higher values indicate a need to control erosion and manage surface water. These differences are due to the shape of the land, the type of rock, the presence of plants, and the amount of rainfall that falls.

A very high drainage density indicates numerous streams with rapid water flow, typically located on hard or steep terrain. These areas have limited groundwater resources, are prone to erosion or flooding, and are unsuitable for wells or intensive farming practices. They need special care. High density (0.74–0.95 km²/km²) leads to significant runoff, with limited infiltration and reduced groundwater, necessitating careful management, especially in areas such as farms or cities. Moderate density (0.95–1.14 km/km²) has a balance of runoff and soaking, which is beneficial for farming and towns due to reduced flooding and erosion. Low density (1.14–1.35 km/km²) means fewer streams and more soaking in, which is beneficial for maintaining groundwater levels.

Very low drainage density means few streams and very porous, cracked rocks that allow water to sink in easily, resulting in high groundwater levels. These places are ideal for replenishing aquifers, collecting water, and effective water management.

Areas with low drainage density are more favourable for groundwater recharge because surface runoff is minimized, allowing for more efficient recharge. Conversely, regions with high drainage density are prone to increased runoff and soil erosion, which can negatively affect both the quantity and quality of groundwater recharge. Therefore, identifying zones with reduced drainage density is essential for effective groundwater management, as these areas generally have higher infiltration rates and greater aquifer recharge potential. This approach is particularly beneficial in arid environments, where water scarcity is common, making the optimization of groundwater recharge essential for sustainable water resource management [29].

Examining the Bwari data reveals that most of the area has a medium drainage density, resulting in steady surface water flow that impacts groundwater recharge, soil loss, and land use planning. Places with very low or very high drainage densities tend to be smaller, exhibiting a mix of water flow patterns across the area. This mix results from the land's shape, type of rock, and the way water moves, all of which work together to determine how water spreads out [30]. High drainage density typically indicates numerous small streams and a higher risk of flooding, as water remains on the surface and doesn't soak in deeply [31]. In contrast, areas with low drainage density allow more water to soak into the ground, slowing the water down and resulting in less runoff, as many watershed studies have shown [32]. This change demonstrates that drainage density is a crucial factor in determining the amount of rainwater that can contribute to groundwater and the likelihood of flooding. Lower drainage densities usually mean more recharge, while higher densities mean more risk of floods because water runs off faster [33].

- *Lineament Density and Groundwater Potential*

To measure lineament density, hillshade analysis and automation were used together. First, several hillshade images were created using ArcGIS, with a sun height of 45° and varying sun angles (0°, 45°, 90°, and 135°). These images were stacked to make the straight features on the land easier to see. Then, lineaments were identified using the PCI Geomatica line detection tool, which detects straight features by analysing changes in brightness. The found lines were then processed in ArcGIS, and how closely they sit together was worked out with the Kernel Density tool, similar to how drainage density was measured:

$$\mathrm{Ld} = \frac{L}{A} \qquad (6)$$

Where Ld is lineament density, L is the total length of lineaments, and A is the area of the study area.

Lineament density quantifies the frequency of linear geological structures, such as faults, joints, and fractures, within a defined area. These structures often function as preferential pathways for groundwater flow and serve as loci for groundwater accumulation. Higher lineament density is typically correlated with increased groundwater potential. Structural discontinuities, detectable on digital elevation models as persistent linear features, generally delineate zones of augmented hydraulic conductivity and groundwater storage [34]. Specifically, areas with higher concentrations of lineaments, particularly those oriented NW-SE to N-S, frequently facilitate groundwater migration, enhance infiltration, and increase the likelihood of identifying productive aquifers [35].

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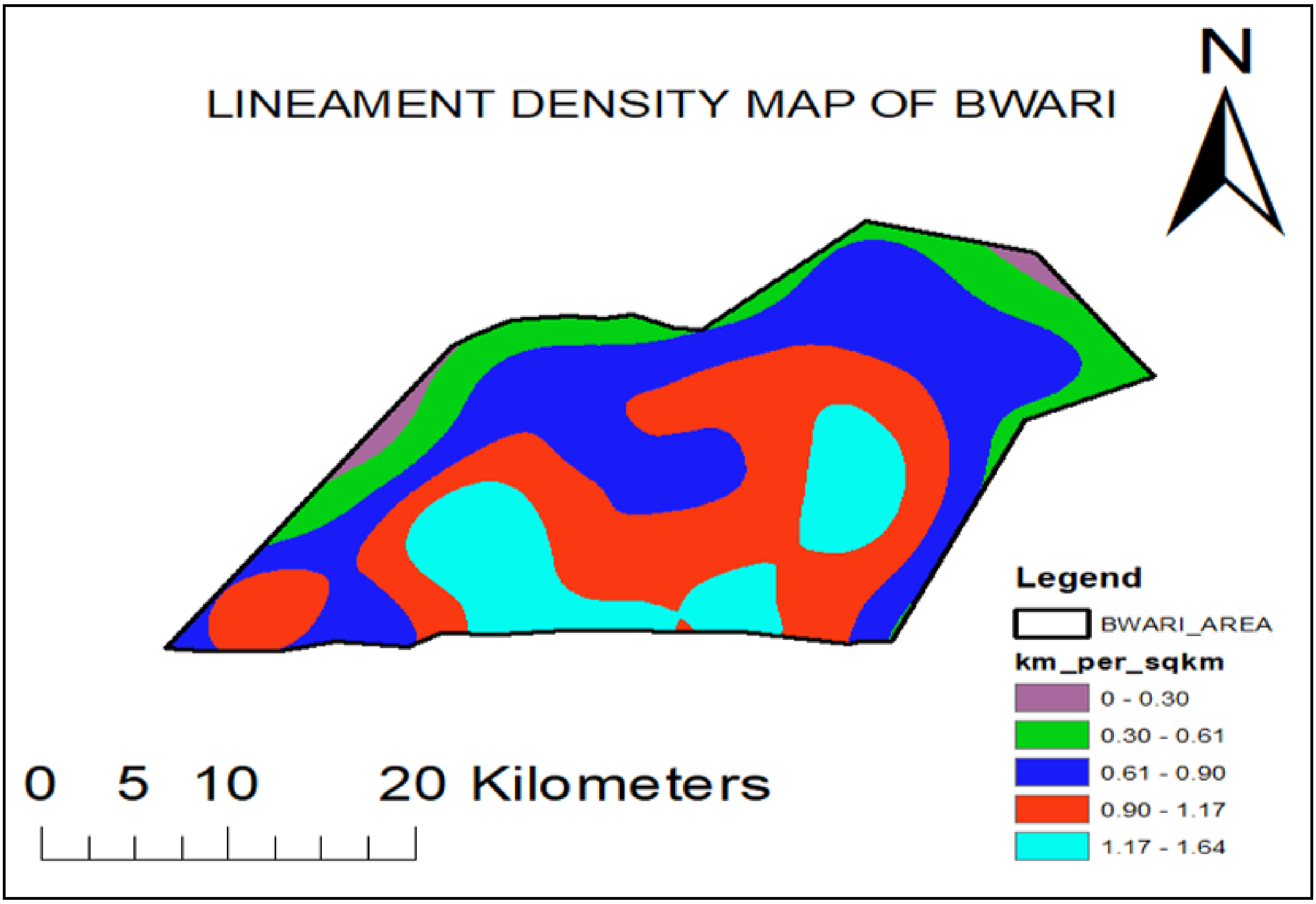

Fig 5 Lineament Density Map of Bwari

Lineament density classification within the Bwari Area Council, as shown in Figure 5 and Table 5, shows pronounced heterogeneity in both structural configuration and groundwater potential. The observed lineament density values range from 0.0 to 1.64 km/km² and are subdivided into five categories: *very low, low, moderate, high,* and *very high.*

The very low lineament density class (0.0–0.30 km/km²) covers approximately 16.45 km² (1.80%). This suggests minimal structural deformation and limited rock fracturing. Such conditions result in low groundwater potential due to restricted secondary porosity and reduced infiltration capacity. These zones are typically underlain by massive, unfractured bedrock, which generally yields minimal groundwater. In contrast, the low lineament density class (0.30–0.61 km/km²) covers 120.53 km² (13.18%). It represents areas with modest fracturing and some structural influence on groundwater movement. These sectors may permit moderate infiltration but have limited groundwater storage. This makes them appropriate for regulated extraction and moderate land-use activities. Consistently, areas with low lineament density have constrained subsurface water mobility and storage, resulting in diminished groundwater potential.

This pattern occurs because lineaments reflect subsurface structural features, such as fractures, joints, and faults. These features appear as linear or slightly curving alignments that are distinguishable from surrounding geological formations [36].

Table 5 Lineament Density Classification in Bwari

Sn	Lineament Density (km/km²)	Area (km²)	Coverage (%)	Classes
1	0 – 0.30	16.45	1.80	Very Low
2	0.30 – 0.61	120.53	13.18	Low
3	0.61 – 0.90	327.64	35.83	Moderate
4	0.90 - 1.17	304.05	33.25	High
5	1.17 – 1.64	145.71	15.94	Very High

The moderate lineament density zone (0.61–0.90 km/km²), which constitutes 327.64 km² (35.83%) of the study area, represents the most prevalent category. This zone is characterized by an optimal balance between subsurface fractures and water infiltration, yielding moderate levels of surface runoff and groundwater recharge. Such conditions are

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favourable for agricultural activities, residential development, and groundwater abstraction. Areas with moderate lineament density are often prioritized for water resource projects due to their reliable groundwater yield [12]. Conversely, excessive fracturing can facilitate rapid subsurface water movement, thereby reducing infiltration potential, while insufficient fracturing impedes groundwater movement and accumulation [37]. Moreover, the spatial configuration and connectivity of fractures within moderate-density zones significantly influence both the direction and magnitude of groundwater flow [38].

The high lineament density zone (0.90–1.17 km/km²), occupying 304.05 km² (33.25%) of the study area, is characterized by a substantial presence of fractures and joints. This structural complexity enhances subsurface water movement and storage, resulting in favourable groundwater conditions. Such areas are well-suited for borehole development and other groundwater extraction initiatives. Regions with high lineament density are typically associated with increased groundwater availability and are thus considered prime targets for groundwater exploration and utilization [12].

The very high lineament density zone (1.17–1.64 km/km²) encompasses 145.71 km² (15.94%) of the total area. These regions exhibit extensive fracturing and ground discontinuities, which significantly facilitate groundwater infiltration and storage. However, such areas may also present geotechnical stability concerns and therefore require careful consideration in land use planning. The abundance of fractures in these zones provides efficient conduits for groundwater recharge, rendering them highly suitable for sustainable groundwater utilization [24]; [38]; [39].

The varying degrees of lineament density within the Bwari Area Council exert differential impacts on groundwater availability. Zones characterized by moderate to very high lineament density, collectively accounting for approximately 85% of the area, are most conducive to groundwater exploration and utilization, whereas areas with low fracture density are marked by limited groundwater presence and reduced permeability. Enhanced fracturing supports increased infiltration and subsurface water movement, thereby promoting groundwater recharge. In such fractured regions, lineaments serve as primary pathways for water flow, particularly within basement rock settings that typically possess limited groundwater reserves [5].

- *Topographic Wetness Index (TWI) and Its Hydrogeological Implications*

The Topographic Wetness Index (TWI) is a hydrological parameter used to quantify the spatial distribution of soil moisture, surface saturation, and potential groundwater recharge zones across a landscape. It expresses the relationship between topography, slope, and water accumulation and is particularly valuable for identifying areas prone to infiltration or runoff [40]. In this study, TWI was derived from Shuttle Radar Topography Mission (SRTM) elevation data using ArcGIS tools. The Slope and Flow Accumulation tools were first employed to generate slope and contribute area raster, respectively. Thereafter, TWI was computed using the following equation:

$$\mathrm{TWI} = \ln\left(\frac{\alpha}{\tan\beta}\right) \tag{7}$$

where α denotes the upslope contributing area obtained from the flow accumulation raster, and β represents the local slope angle in radians. Thus, regions with large upslope contributing areas and gentle slopes (smaller β values) exhibit higher TWI values, indicating greater potential for soil moisture accumulation and groundwater recharge and the computation was performed using the Raster Calculator in ArcGIS, following the established methodology of [41].

The Specific Catchment Area (a), derived from the digital elevation model (DEM), quantifies the upslope area contributing surface flow to a point. Its value depends on the chosen flow routing algorithm (single or multiple flow direction). Areas with higher contributing areas and gentle slopes tend to accumulate more moisture and display high TWI values, whereas low TWI values correspond to steeper, well-drained locations with reduced infiltration potential.

TWI effectively integrates topographic characteristics to assess soil wetness and water distribution patterns. It serves as a quantitative indicator of surface saturation, providing insight into the hydrological behaviour of the terrain. The index is widely used in groundwater potential mapping, wetland delineation, runoff modelling, and ecosystem assessments, where it helps predict zones of saturation and water retention [42]; [43]; [44]. Moreover, TWI has been applied in understanding vegetation dynamics, soil physicochemical processes, and land-use change impacts, offering an integrated perspective of topography-driven hydrological processes [41]; [9]. However, the traditional TWI model presents a static representation of hydrological conditions and does not fully capture temporal variations in soil moisture or dynamic recharge events [45]; [46]; [47].

By quantifying the interaction between terrain form and hydrological response, TWI allows the identification of zones favourable for infiltration, water harvesting, and groundwater recharge [48]. Consequently, it serves as an essential analytical tool for integrating surface morphology with subsurface hydrology, thereby supporting sustainable groundwater resource management. Since it assesses the probability of water accumulation based on local slope and upslope area, TWI serves as a critical tool for mapping regions with elevated groundwater potential [44].

In this study, the TWI evaluated for the Bwari area (see Fig. 6) was classified into five distinct zones, as presented in Table 6

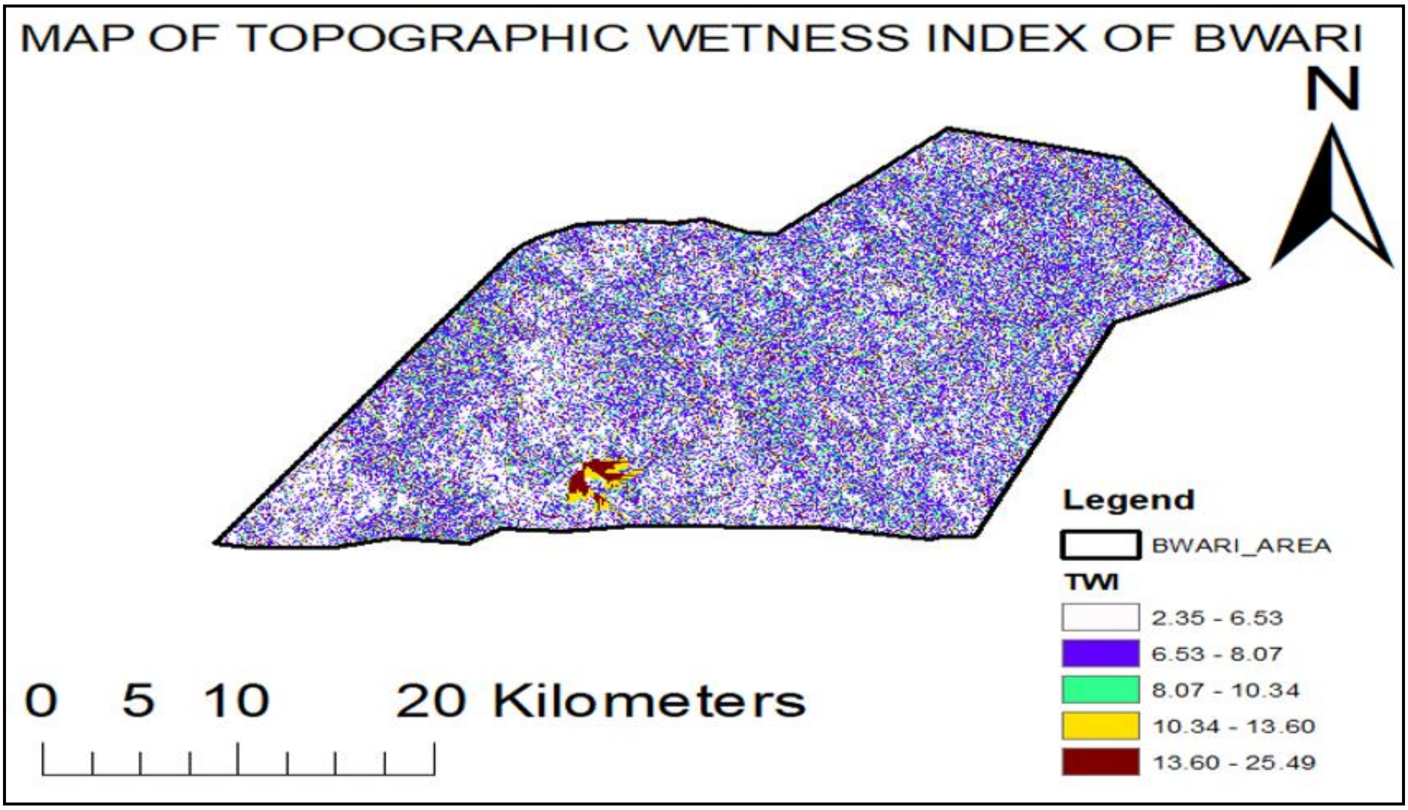

Fig 6 Topographic Wetness Index Map of Bwari

➢ *TWI Classification and Spatial Distribution in Bwari Area Council*

Within the study area, TWI values range from 2.35 to 25.64, enabling classification into five distinct categories; very low, low, moderate, high, and very high as presented in Table 6 and illustrated in Figure 6. This classification provides a spatial framework for evaluating how topographic and hydrological variations influence groundwater recharge across Bwari Area Council.

Table 6 Topographic Wetness Index (TWI) Classification in Bwari

Sn	TWI	Area (km^2)	Coverage (%)	Classes
1	2.35 – 6.53	334.28	36.66	Very Low
2	6.53 – 8.07	345.46	37.89	Low
3	8.07 – 10.34	147.38	16.16	Moderate
4	10.34 – 13.60	62.84	6.89	High
5	13.60 – 25.64	21.84	2.40	Very High

- *Very Low TWI (2.35–6.53)*

The very low TWI class covers approximately 334.28 km² (36.66%) of the study area and is associated with steep slopes and elevated terrains. These areas experience rapid surface runoff, minimal water retention, and low soil moisture, making them unsuitable for groundwater recharge or intensive agriculture. The steep topography enhances erosion risk and surface instability, particularly during heavy rainfall events, marking these zones as runoff-generating regions rather than recharge areas.

- *Low TWI (6.53–8.07)*

The low TWI class constitutes the largest portion of the study area, covering 345.46 km² (37.89%). These areas exhibit gentle to moderate slopes with limited surface saturation and moderate infiltration potential. Although groundwater recharge here is modest, vegetative cover and soil conservation measures can enhance infiltration capacity [49]; [42]; [24]. Effective land management in these regions should focus on erosion control and slope stabilization to reduce surface runoff.

- *Moderate TWI (8.07–10.34)*

The moderate TWI zone spans 147.38 km² (16.16%), reflecting a hydrological balance between runoff and infiltration. Such areas maintain moderate soil moisture levels and are suitable for agriculture, settlements, and managed groundwater extraction. The equilibrium between surface and subsurface flow supports vegetation and ecological stability. Integrating moderate to high TWI areas with geophysical parameters enhances the delineation of groundwater potential zones [9]; [24].

- *High TWI (10.34–13.60)*

The high TWI class occupies 62.84 km² (6.89%) and is characterized by gentle slopes, valley bottoms, and

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depressions with substantial water accumulation. These conditions promote increased infiltration, higher soil saturation, and enhanced groundwater recharge potential. Such areas are favourable for shallow well construction and wetland conservation, though they may experience seasonal waterlogging [49]; [42].

- *Very High TWI (13.60–25.64)*

The very high TWI class, covering 21.84 km² (2.40%), corresponds to floodplains, wetlands, and low-lying zones. These areas exhibit maximum surface saturation and minimal drainage, making them highly significant for aquifer recharge but less suitable for permanent settlement due to flooding risks and soil instability. Their management is crucial for wetland preservation and water retention enhancement.

➢ *Hydrological Interpretation and Implications*

The spatial distribution of TWI across the Bwari Area Council indicates that nearly 75% of the land area falls within the very low to moderate wetness categories, reflecting rapid infiltration, limited saturation, and moderate recharge potential. In contrast, high and very high TWI zones, though smaller in extent, play a pivotal role in sustaining groundwater recharge and maintaining hydrological balance across the landscape. This pattern reveals a natural hydrological gradient from runoff-dominated uplands to recharge-prone lowlands that governs the area's groundwater dynamics.

Integrating TWI with other hydrogeological parameters such as lithology, slope, drainage density, and lineament distribution provides a comprehensive understanding of groundwater recharge processes. Consequently, TWI serves not only as a topographic descriptor but also as a proxy for subsurface hydrological behaviour, making it indispensable for groundwater potential mapping, watershed management, and sustainable land-use planning [50].

➢ *Rainfall and Groundwater Potential*

Consolidated monthly rainfall measurements from 2023 to 2024 was used to create an annual rainfall distribution map for the study area. Annual rainfall in the Bwari Area Council falls into two categories, highlighting the region's climate and hydrology. Rainfall ranged from 1,220 mm to 1,353 mm per year, indicating a humid tropical climate shaped by north-central Nigeria's seasonal precipitation.

This categorization distinguishes between high and very high rainfall zones, each with specific hydrological and environmental impacts (see Figure 7 and Table 7).

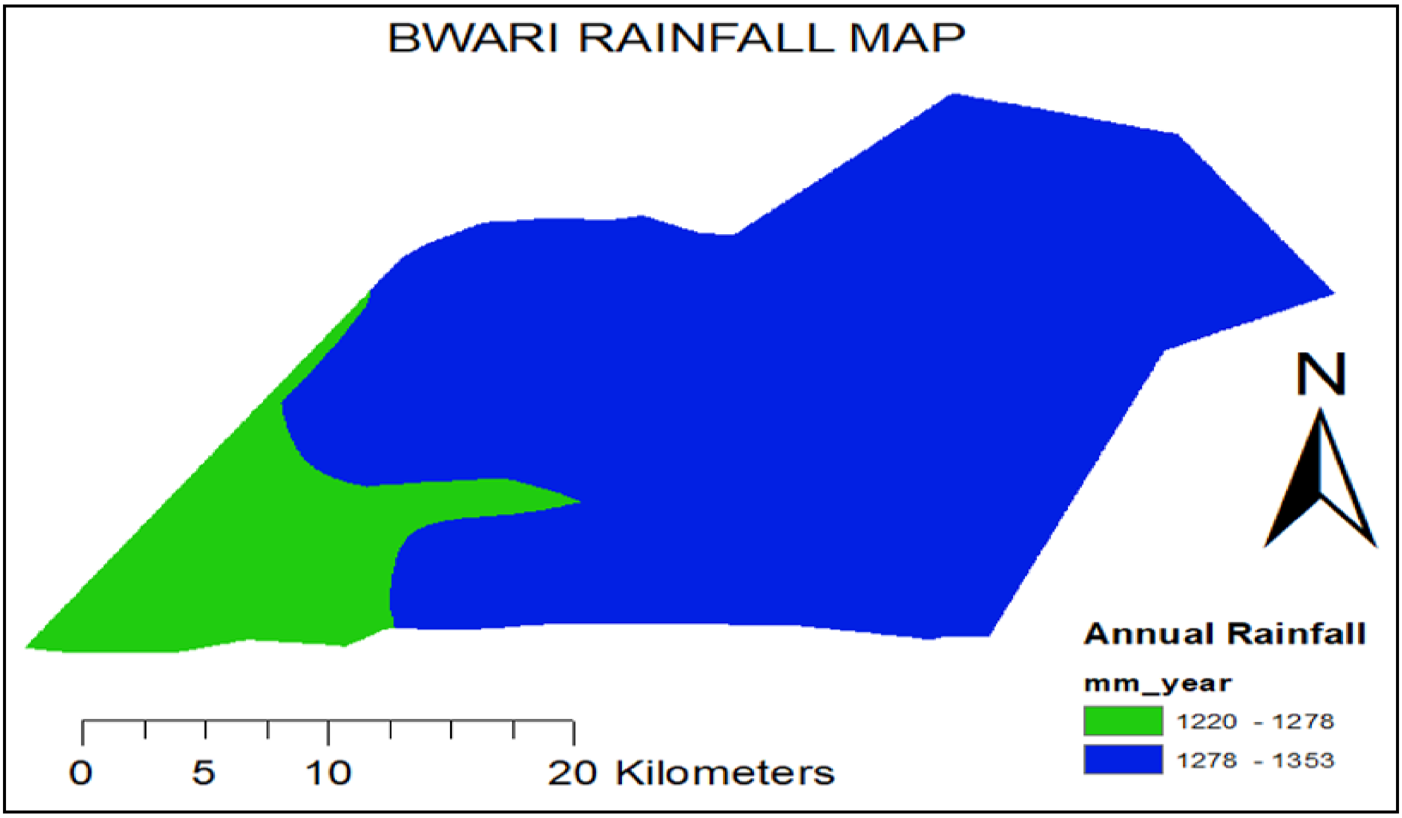

Fig 7 Annual Rainfall Map of Bwari (September 2023 – August 2024)

The high rainfall zone, receiving between 1,220 and 1,278 mm annually, encompasses approximately 202.47 km², constituting 22.14% of the study area (see Table 7). This zone is predominantly situated in moderately elevated and transitional topographies. In these areas, precipitation primarily generates substantial surface runoff and moderate infiltration, thereby contributing to the recharge of shallow aquifers. However, the comparatively lower rainfall limits the potential for deep groundwater recharge. Consequently, the implementation of effective soil and water management practices in these regions is essential to improve water retention and minimize erosion.

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Table 7 Annual Rainfall Classification in Bwari

Sn	Annual Rainfall (mm/year)	Area (km^2)	Coverage (%)	Classes
1	1220 – 1278	202.47	22.14	High
2	1278 – 1353	1210.64	77.86	Very High

The very high rainfall zone (1,278–1,353 mm/year) encompasses 1,210.64 km², accounting for approximately 77.86% of Bwari Area Council. The dominance of this zone demonstrates that the region experiences considerable and persistent rainfall, supporting groundwater recharge, surface water resources, and vigorous vegetation growth. Abundant moisture enhances agricultural productivity and sustains aquifer replenishment. Nonetheless, these areas are also susceptible to issues such as flooding, erosion, and seasonal waterlogging, especially in low-lying or poorly drained landscapes.

In summary, the Bwari Area Council is characterized by predominantly high to very high rainfall, which creates optimal conditions for groundwater recharge, agricultural development, and ecological sustainability. However, the substantial precipitation levels highlight the necessity of strategic land-use planning and watershed management to address and minimize flood hazards and promote the sustainability of groundwater resources.

Annual rainfall a key determinant of groundwater potential, as it regulates the volume of water available for aquifer recharge. Regions with abundant rainfall generally exhibit greater groundwater replenishment prospects due to higher rates of infiltration, while areas with limited rainfall face constraints in groundwater renewal. The extent and timing of recharge are influenced by both hydrogeological and climatic factors, with increased precipitation closely linked to enhanced recharge rates [51]. The balance between rainfall and evapotranspiration further affects total groundwater recharge, emphasizing the impact of climate variability in aquifer replenishment [52]. In more arid settings, a higher proportion of rainfall is lost to evaporation, diminishing the contribution to the streamflow and groundwater recharge [53].

➢ *Land Use/Land Cover (LULC) and Groundwater Potential*

The Land Use/Land Cover (LULC) data for Bwari were obtained by extracting relevant sections from both the national and Federal Capital Territory (FCT) LULC datasets using clipping techniques.

Land use and land cover (LULC) greatly influence groundwater recharge. In urban areas, impervious surfaces restrict water infiltration, reducing groundwater availability. This happens when permeable, natural surfaces are replaced by materials that hinder water percolation. As a result, recharge rates decrease, and surface runoff increases [54]. These hydrological changes not only reduce groundwater reserves but also increase the risk of contamination. Higher pollutant concentrations in runoff can affect water quality [55]. In contrast, areas with natural vegetation and permeable soils support greater infiltration and enhance recharge [56]. Urban regions with numerous impervious surfaces exhibit lower infiltration capacities, which restrict groundwater replenishment [57]. Forested areas maintain steady water flow and ongoing percolation. However, agricultural lands may influence slope stability due to increased soil moisture beneath vegetation [58].

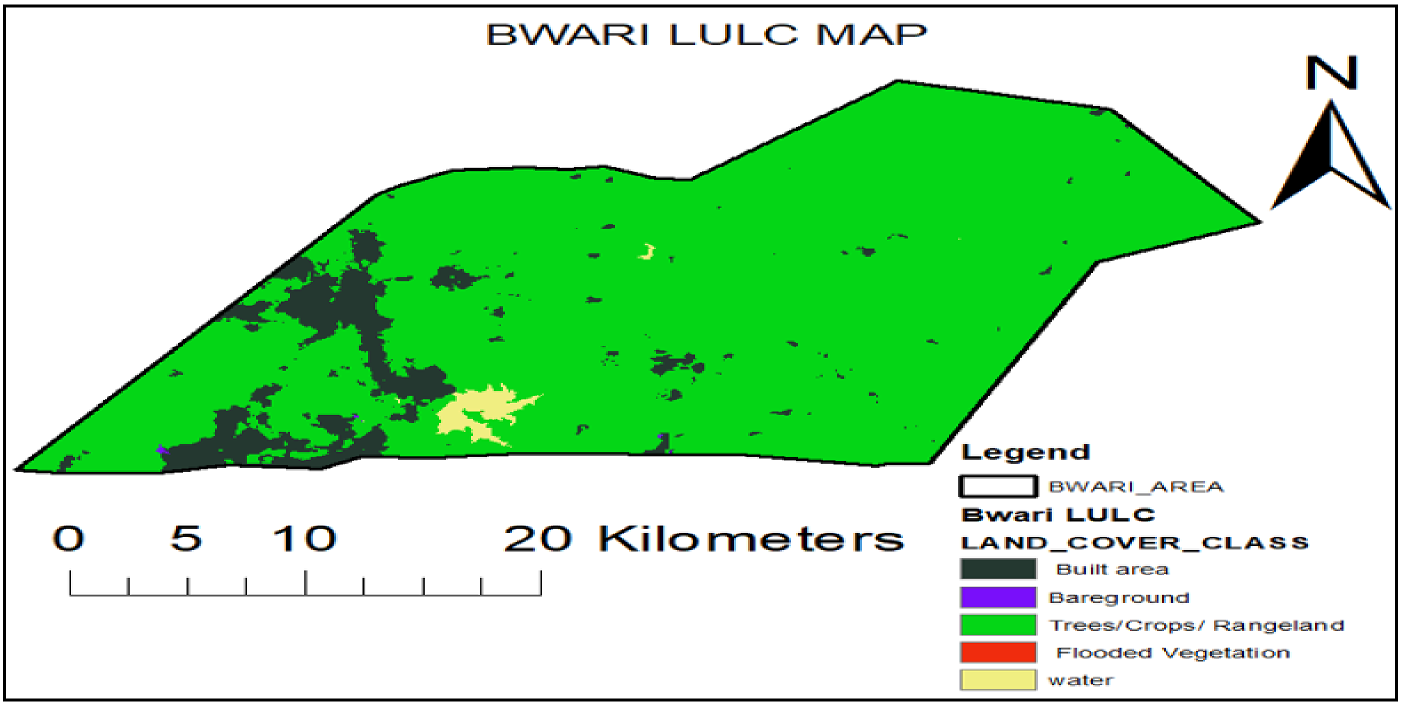

Fig 8 Land Use/Land Cover (LULC) Map of Bwari

The Land Use/Land Cover (LULC) classification for Bwari Area Council offers a detailed view of how surface features are distributed and their impact on environmental and hydrological processes (Figure 8). The classification encompasses five main categories: built-up areas, bare ground, trees/crops/rangeland, and flooded vegetation. Together, these categories define the region's landscape, ecological balance, and groundwater recharge potential.

Table 8 Land Use/Land Cover Classification in Bwari

Sn	Land cover classes	Area (km^2)	% Coverage
1	Buit area	73.7643	8.023542
2	Bare Ground	0.3041	0.033073
3	Trees/Crops/Rangeland	835.6720	90.89826
4	Flooded Vegetation	0.0006	0.000063
5	Water	9.6077	1.045057

Built-up areas occupy approximately 73.76 km², representing 8.02% of the total land mass. These regions consist of residential, commercial, and infrastructural developments, such as roads and urban settlements (see Table 8). The prevalence of impervious surfaces in these zones inhibits water infiltration and promotes increased surface runoff, thereby reducing groundwater recharge. Consequently, built-up regions are more vulnerable to flooding, erosion, and insufficient drainage, particularly during periods of heavy rainfall. The ongoing expansion of urban areas underscores the importance of implementing sustainable urban planning and robust stormwater management strategies to address associated hydrological and environmental challenges.

In contrast, bare ground accounts for only 0.30 km² (0.03%) of the overall area, indicating a minimal presence of unvegetated soil surfaces. Such areas are likely associated with recently cleared or eroded land parcels. The existence of bare ground can contribute to increased surface runoff and heightened susceptibility to soil erosion, particularly on steep gradients. Nevertheless, the very limited extent of bare soils suggests that land degradation due to exposed surfaces is not a major environmental concern in this context.

The trees, crops, and rangeland category constitutes the dominant land cover, encompassing 835.67 km², or 90.90% of the total area. The extensive vegetative cover implies a landscape characterized predominantly by natural and agricultural environments. This configuration enhances opportunities for water infiltration, evapotranspiration, and groundwater recharge. The inclusion of cropland and rangeland reflects sustainable land management practices that support both subsistence and commercial agriculture. Vegetation in these areas contributes to soil stabilization, moisture retention, and flood mitigation, highlighting its ecological significance in maintaining the region's hydrological balance.

Flooded vegetation covers a mere 0.0006 km² (0.00006%) of the region, corresponding to small, isolated wetland areas or zones subject to seasonal inundation. Despite their limited spatial extent, these ecosystems play a critical role in water purification, flood regulation, and the conservation of biodiversity. Additionally, they act as transient groundwater recharge zones, particularly during episodes of heavy rainfall.

Water bodies occupy approximately 9.61 km², representing 1.05% of the total land area. These features include rivers, streams, ponds, and reservoirs, which are integral to the Bwari's surface water resources. Such water bodies facilitate interactions between surface water and groundwater, fulfil domestic and agricultural water needs, and contribute to local climate regulation. Nevertheless, they remain vulnerable to contamination and sediment accumulation, particularly because of runoff from urban and agricultural sources in adjacent areas.

In summary, the land cover profile of the area is diverse but predominantly characterized by vegetation (trees, crops, and rangeland). This predominance reflects strong ecological stability and a significant capacity for groundwater recharge.

➢ *Geological Map and Groundwater Potential*

The geological map obtained from NGSA was digitized to extract rock types. These formations in the study area influence groundwater potential, as they vary in their ability to store and transmit water (Figure 9).

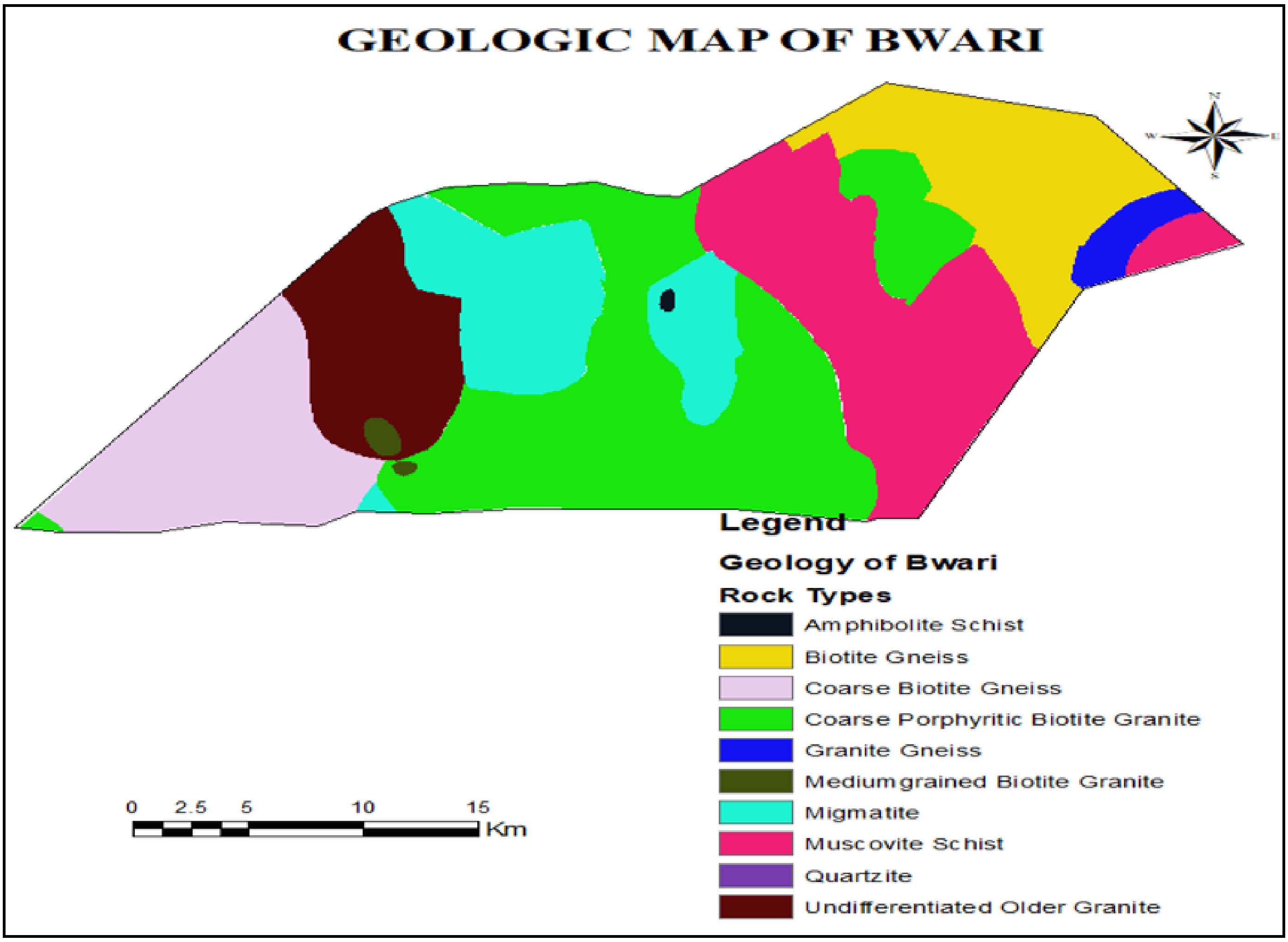

Fig 9 Geological Map of Bwari Area Council

Conversely, lithologies such as sandstone have high porosity and permeability. These properties make them well-suited for groundwater accumulation and recharge. In contrast, less permeable rocks such as certain granites and schists generally have reduced groundwater potential. The development of fractures within these geological units can significantly increase their permeability and storage capacity. This, in turn, improves groundwater potential. For example, granite typically yields moderate to low amounts of groundwater due to its minimal primary porosity. This restricts its aquifer properties. Nonetheless, extensive fracturing and weathering can substantially enhance granite's capacity to store and transmit water. As a result, granite may produce notable groundwater yields [59].

Table 9 Rock Types in Bwari

Sn	Rock Types	Area (km^2)	Coverage (%)
1	Amphibolite Schist	0.883	0.097
2	Biotite Gneiss	114.679	12.581
3	Coarse Biotite Gneiss	15.851	1.739
4	Coarse Porphyritic Biotite Granite	113.991	12.505
5	Granite Gneiss	181.021	19.859
6	Medium Grained Biotite Granite	121.138	13.289
7	Migmatite	4.014	0.440
8	Muscovite Schist	274.497	30.113
9	Quartzite	85.474	9.377
10	Undifferentiated Older Granite	0.007	0.001

From Table 9 above, the Bwari geology revealed dominant rock types are Muscovite Schist, which is the most prevalent at 274.497 km² (30.11%); Granite Gneiss at 181.021 km² (19.86%); Medium Grained Biotite Granite at 13.29%; and Biotite Gneiss at 12.58%. Following the dominant types, moderately represented types include Coarse Porphyritic Biotite Granite at 12.51%, Quartzite at 9.38%, and Coarse Biotite Gneiss at 1.74%.

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Finally, minor rock types are present in much smaller proportions: Migmatite accounts for 0.44%, Amphibolite Schist is very limited at 0.10%, and Undifferentiated Older Granite is almost negligible, covering just 0.007 km² (0.001%).

The predominance of schists and gneisses suggests a region with significant metamorphic activity. Additionally, the high muscovite schist content may indicate conditions favourable for the formation of mica-rich rocks, possibly due to medium to high-grade metamorphism. The high muscovite schist content may indicate conditions favourable for the formation of mica-rich rocks, possibly due to medium to high-grade metamorphism. Furthermore, the presence of several granite and gneiss types of points to multiple intrusive and metamorphic events. In contrast, the low coverage of amphibolite schist and migmatite suggests these are less common, possibly occurring in localized zones or as minor lithological variants. In contrast, the low coverage of amphibolite schist and migmatite suggests these are less common, possibly occurring in localized zones or as minor lithological variants. In contrast, the low presence of amphibolite schist and migmatite suggests these rocks are less common, likely found only in specific areas or as minor types. Amphibolite is a rare rock that appears as layers or lenses within schists, characterized by fine grains and distinct layering [60].

The lithological composition of the study area predominantly consists of metamorphic and igneous rocks, including various types of schists, gneisses, granites, quartzite, migmatite, and amphibolite schist. These formations are characteristically hard, dense, and crystalline, with low primary porosity and permeability, resulting in limited natural groundwater storage. Consequently, groundwater availability is largely confined to secondary features such as fractures, joints, and weathered zones. While schists, gneisses, and certain granites can yield moderate amounts of groundwater if extensively fractured or weathered, their general potential remains low unless these secondary structures are well developed. Overall, the region's groundwater resources are primarily dependent on the presence and extent of such secondary porosity features. The relationship between groundwater yield and geological factors is complex and multifaceted. Specifically, groundwater yield still depends on the extent of weathering and fracturing. In metamorphic regions, regolith and fracture zones constitute the principal aquifers responsible for groundwater storage and transmission [61].

➤ *Soil Type and Groundwater Potential*

The soil map of the Federal Capital Territory (FCT) was generated from the Food and Agriculture Organization (FAO) soil map through the application of clipping techniques. Subsequently, the soil map for Bwari was delineated from the broader FCT soil map to provide finer spatial resolution relevant to the study area. Lithosols and Ferric Luvisols constitute the dominant soil types within the Bwari Area Council. These soils exert considerable influence on agricultural practices, infiltration dynamics, and groundwater recharge potential. The spatial distribution of these soil types is largely determined by the region's underlying geology, topographical variation, and prevailing climatic conditions (see Figure 10).

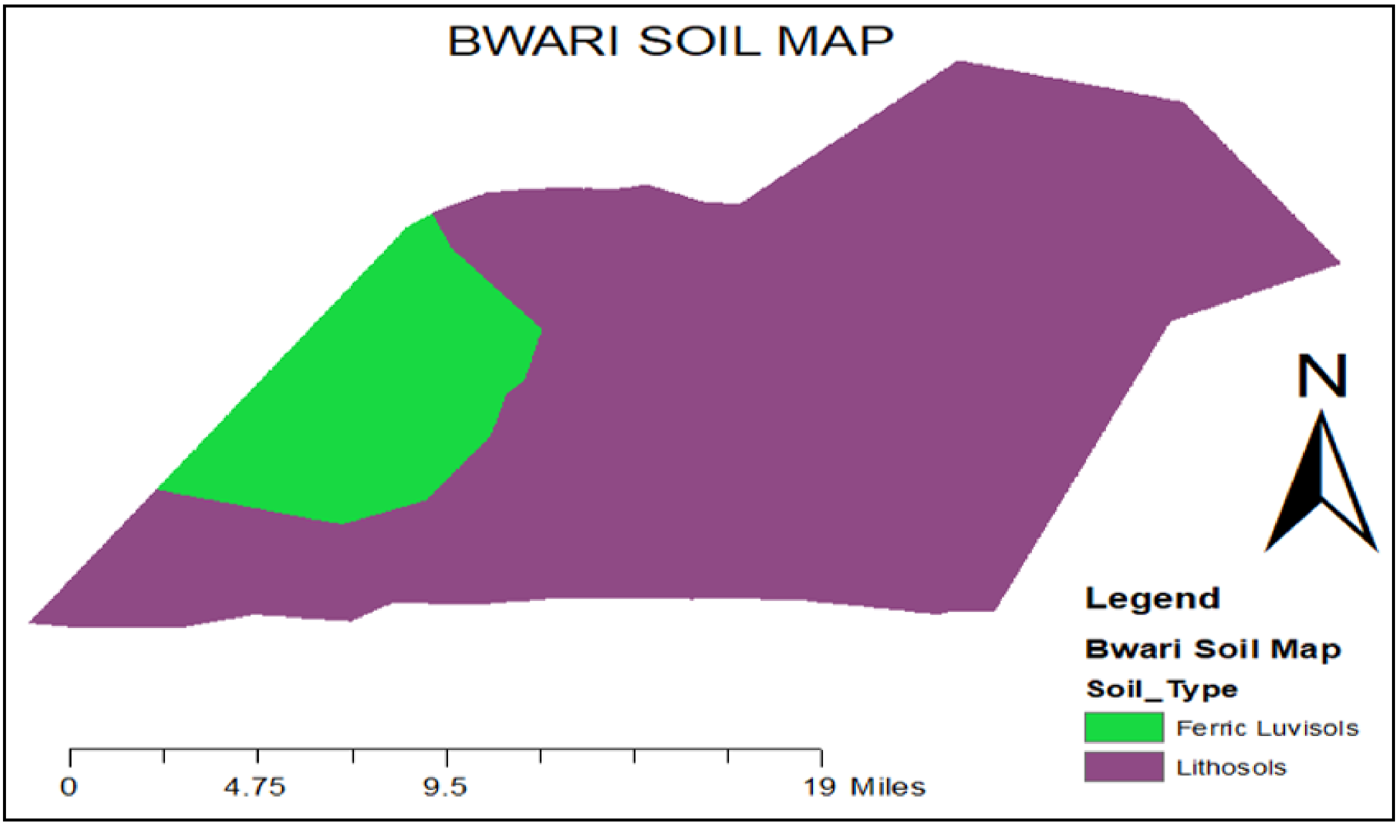

Fig 10 Soil Type Map of Bwari Area Council

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Lithosols cover about 780.75 km² (85.39%) of the Bwari area council. These are the main types of soil in this area. Lithosols are thin, rocky, and not well-formed (see Table 10). They are common on hills with hard, rocky ground. These soils do not let much water in or hold much water. This means they do not store much water below the surface. They can also wash away easily during heavy rain or when there are few plants. For farming, Lithosols are not very fertile. Farmers need to incorporate natural fertilizers and plant crops across hillsides to prevent erosion and maintain soil stability. Because Lithosols are so common, most of Bwari is situated on rocky or high ground, which aligns with the area's geology.

Table 10 Soil Types in Bwari

Sn	Soil Type	Area (km^2)	Coverage (%)
1	Lithosols	780.75	85.39
2	Ferric Luvisols	133.63	14.61

Ferric Luvisols cover approximately 133.63 km² (14.61%) and are the second most common soil type. Their significant iron content and good drainage make them favorable for crops that require well-aerated roots. Because these soils are clay-rich, they hold and gradually release water, directly supporting efficient groundwater recharge and a reliable water supply for agriculture, particularly during the rainy season.

The Bwari Area Council is predominantly characterized by Lithosols; rocky, elevated land with limited groundwater storage. Ferric Luvisols, though less widespread, are better for farming and water management. The soil distribution highlights the need for erosion control, tree planting, and sustainable use of Ferric Luvisol areas to replenish groundwater. Luvisols have a subsoil rich in clay and nutrients, which makes them good for farming, though they need to be managed with care. Ferric Luvisols, on the other hand, have reddish or yellowish soil that drains well because of iron, but they can sometimes be a bit acidic or get waterlogged [62].

➢ *Analytical Hierarchy Process*

The Analytic Hierarchy Process (AHP) was employed to evaluate groundwater potential in the Bwari area council of the Federal Capital Territory (FCT) using eight distinct criteria: Rainfall, Geology, Slope, Drainage Density, Land Use/Land Cover, Lineament Density, Soil Type, and Topographic Wetness Index (TWI). Each criterion contributes to the assessment of groundwater potential, with its relative significance determined through the AHP framework.

The weighting procedure reveals that each criterion was allocated a distinct weight corresponding to its influence on groundwater potential in the study area. The assigned weights range from 3.8% to 34.2%, with Rainfall (34.2%), Geology (23.7%), and Slope (13.7%) identified as the most significant determinant determinants.

The analysis produced an eigenvalue (λ) of 8.449, closely approximating the total number of criteria (8), indicating consistency in the pairwise comparisons conducted within the AHP. Moreover, a consistency ratio (CR) of 4.6%, substantially below the acceptable threshold of 10%, further confirms the reliability of the comparison process.

➢ *Assigned and Normalized Weights of Different Features*

The procedure for assigning and normalizing weights in this study was informed by a broad array of international expert research on hydrological challenges. Saaty's Analytical Hierarchy Process (AHP) [63] was utilized to determine the weights attributed to different thematic layers and their respective features in the mapping of groundwater potential zones (GWPZ). The following steps outline the calculation of the consistency ratio:

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.

➢ *Computation of the consistency ratio (CR)*

$CR = \frac{CI}{RCI}$, where RCI refers to a random consistency index (see Table 2).

Eight thematic layers; Rainfall, Geology, Slope, Drainage Density, Land Use/Land Cover, Lineament Density, Topographic Wetness Index, and Soil Type were examined. Vector data were converted to raster format to facilitate integration with other raster-based thematic layers in the GIS modelling workflow. A resampling procedure was conducted to standardize the resolution across all thematic layers.

Each thematic layer was allocated a weight reflecting its relative influence on groundwater resources.

Table 11 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 12 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

Each of the values in column Sum A1 (table 12) is calculated using the values in the first row of table 10, which are multiplied from left to right as demonstrated below.

= (1*3*3*5*5*5*5*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, λ-max = 67.561/8 = 8.445, n = 8 and RCI = 1.41 (From table 2)

Consistency Index

$CI = \frac{\lambda_{max}-n}{n-1} = \frac{8.445-8}{8-1} = \frac{0.445}{7} = 0.06367$.3 Consistency Ratio

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

A consistency ratio of 0.0451, being below the 0.1 threshold, demonstrates that the pairwise comparisons exhibit an acceptable level of consistency.

Accordingly, weights of 0.3327 (33.27%), 0.2372 (23.72%), 0.1383 (13.83%), 0.0946 (9.46%), 0.0709 (7.09%), 0.0494 (4.94%), 0.0384 (3.84%), and 0.0384 (3.84%) were assigned to the variables Land Use/Land Cover, Soil Type, Geology, Rainfall, and Topographic Wetness Index (TWI), respectively.

➢ *Groundwater Potential Zones Calculation*

All parameters were resampled to a 30-meter spatial resolution to maintain consistency and facilitate analysis. Weights reflecting the relative importance of each parameter for groundwater potential were assigned using the Analytical Hierarchy Process (AHP), a structured technique for organizing and analysing complex decisions. Parameters were classified and rated according to their influence on groundwater potential, with higher scores denoting greater significance (refer to Tables 4.3a and 4.3b). Subsequently, a weighted overlay analysis method that assigns values to spatial data layers based on their relative contribution; was conducted in ArcMap 10.7.1, integrating all parameters to produce the groundwater potential map for the study area.

Table 13 (A) 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	
2	Geological Map	Amphibolite Schist	Poor	2	23.7
		Biotite Gneiss	Moderate	3	
		Coarse Biotite Gneiss	Moderate	3	
		Coarse Porphyritic Biotite Granite	Moderate	3	
		Granite Gneiss	Moderate	3	
		Medium Grained Biotite Granite	Poor	2	

		Migmatite	Good	4	
		Muscovite Schist	Poor	2	
		Quartzite	Moderate	3	
		Undifferentiated Older Granite	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	

Table 13 (B) Influencing Factors, Potentials for Groundwater, Rate and Normalized Weights

Sn	Influencing Factors	Category (Classes)	Potentiality for groundwater storage	Rating (r)	Normalized Weight
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		Bare ground	Poor	2	7.1
		Rangeland	Moderate	3	
		Crops	Moderate	3	
	LULC	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
		Ferric Luvisols	Moderate	3	

The Analytical Hierarchy Process (AHP), integrated with Geographic Information Systems (GIS) and Remote Sensing (RS), provides a systematic approach to mapping groundwater potential by evaluating multiple factors that influence groundwater recharge. For the Bwari area council of FCT, Abuja, a groundwater potential map (Figure 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.

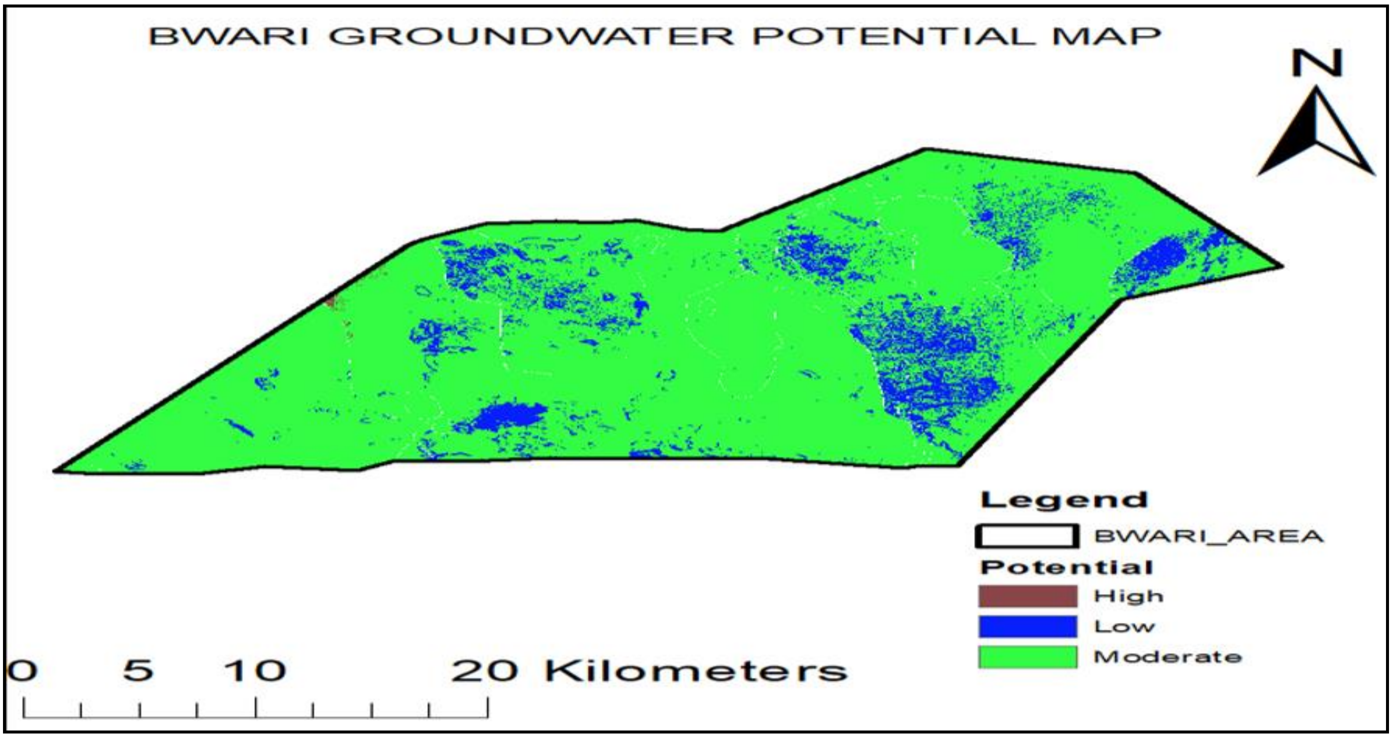

Fig 11 Groundwater Potential Zone of Bwari

Table 14 Groundwater Potential of Bwari Area Council (GIS/RS)

Sn	Potential	Area(km2)	Coverage (%)
1	Low	0.65	0.07
2	Moderate	608.63	66.90
3	High	300.51	33.03

Table 14 shows the spatial distribution of groundwater potential zones in Bwari Area Council, determined using Geographic Information Systems (GIS) and Remote Sensing (RS), which combine data layers (thematic layers) such as geology (rock types), geomorphology (landforms), drainage density (concentration of streams), slope (inclination of the land), lineament density (frequency of geological fractures), and land use/land cover (how the land is used or covered, such as by vegetation or buildings). The classification into *low*, *moderate*, and *high* potential zones reflects the relative ability of areas to store and transmit groundwater, based on conditions at the surface and below ground. These findings offer a broad understanding of the region's hydrogeological (related to groundwater) framework and highlight areas suitable for sustainable groundwater exploration and development.

➢ *Low Groundwater Potential Zone*

The low groundwater potential zone covers an area of 0.65 km², or approximately 0.07% of the total area. This small proportion means areas with poor groundwater potential are spatially insignificant in the Bwari Area Council. Such zones are typically associated with impermeable crystalline rocks (rocks that do not allow water to pass through), steep slopes (land with very inclined surfaces), high drainage density (many streams close together), and limited weathering (little breakdown of rocks). These factors inhibit infiltration (the process by which water soaks into the ground) and reduce groundwater recharge (the replenishment of groundwater). The scarcity of low-potential areas shows that most of the terrain has favourable hydrological (water-related) and geological conditions, with only limited regions where structural or lithological (rock type) barriers restrict groundwater accumulation.

➢ *Moderate Groundwater Potential Zone*

The moderate potential zone, covering 608.63 km² or 66.90% of the total area, suggests that most of the Bwari has moderately favourable groundwater conditions. Features like moderately fractured bedrock, gentle slopes, and medium drainage densities contribute to this. These transitional zones offer opportunities for improved yield through artificial recharge or strategic borehole placement.

➢ *High Groundwater Potential Zone*

The high groundwater potential zone covers 300.51 km², or 33.03% of the total area, indicating highly favourable conditions in about one-third of the study area. Characterized by thick overburden, fractured bedrock, low drainage density, and gently undulating topography, these zones are prime targets for groundwater development due to the significant secondary porosity created by weathering.

➢ *Spatial Implications and Hydrogeological Interpretation*

Moderate and high-potential zones together account for 99.93% of the area, highlighting Bwari's favourable hydrogeological settings. The small, low-potential zone reflects localized groundwater scarcity, likely due to geological variations in the area. The extensive moderate and high potential areas suggest productive aquifers; their spatial

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pattern can guide strategic water resource planning, borehole siting, and land-use decisions.

➢ *Comparative Analysis*

The GIS/RS-derived zones align with the area's structural and lithological framework. High-potential areas coincide with regions of intense weathering, while moderate areas are transitional between fractured and intact bedrock. Using GIS and remote sensing offers a spatially coherent, multi-parameter assessment, reducing uncertainty. The proportion of high-potential areas (33.03%) matches previous findings for similar terrains. Overall, Bwari is predominantly moderate to high potential (99.93%); high zones improve yield and storage, moderate zones offer scope for management, and low potential is minimal, confirming generally favourable hydrogeological conditions.

In conclusion, the findings affirm that the Bwari Area Council has strong groundwater development potential. Future water resource planning should prioritize high-potential areas and ensure the protection and recharge of moderate zones to optimize water resources.

➢ *Vertical Electrical Sounding VES Results*

A Vertical Electrical Sounding (VES) survey was conducted at twenty-three locations (BWR-01 to BWR-23) in the Bwari Area Council to evaluate near surface geology and groundwater potential. Resistivity data collected with the Schlumberger electrode array were interpreted to identify geoelectric layers, determine lithological composition, and evaluate aquifer potential.

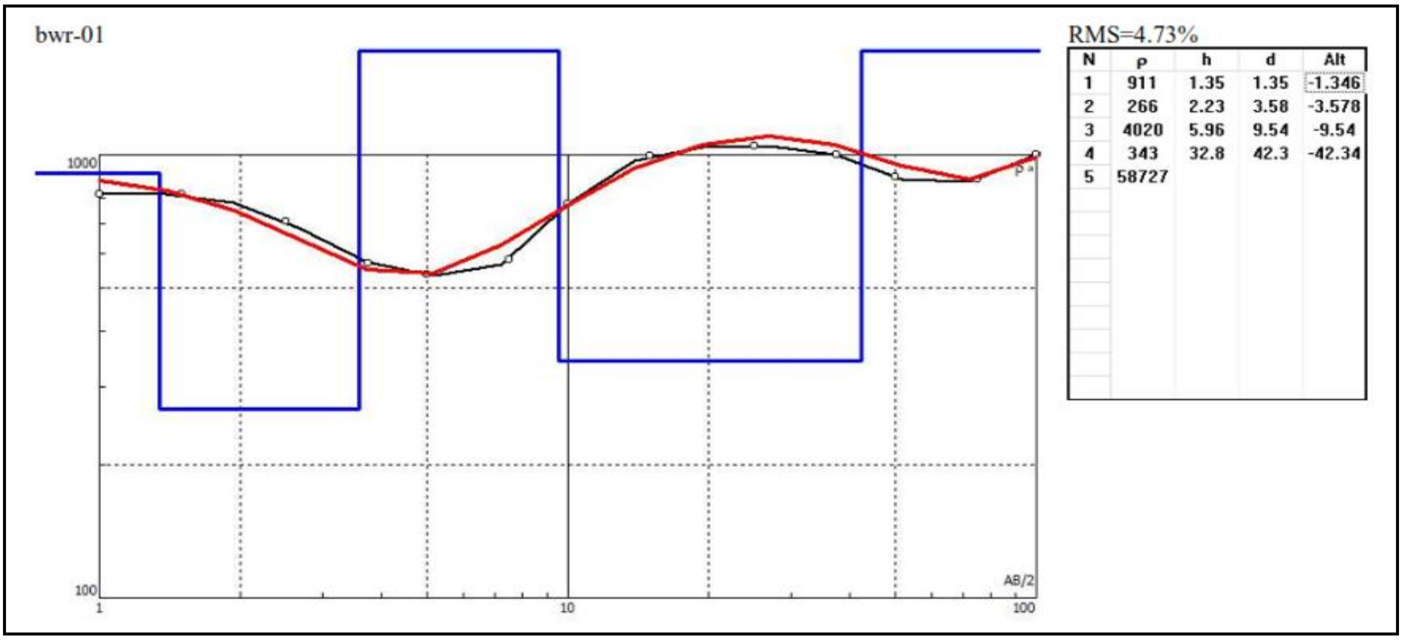

Fig 12 Typical Interpretation of VES BWR-01

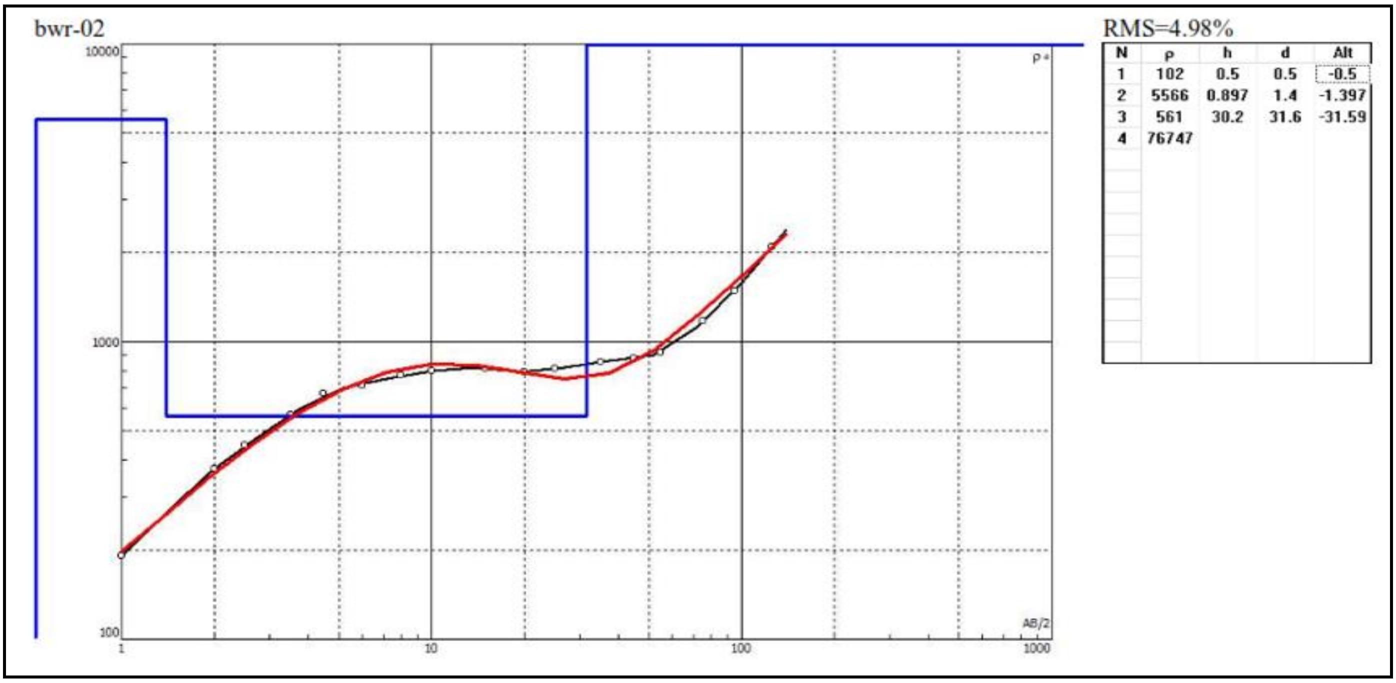

Fig 13 Typical Interpretation of VES BWR-01

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➢ *The VES Interpretations*

- *BWR01*

The vertical electrical sounding (VES) curve displays alternating high and low resistivity layers. The topsoil (695 Ωm, 1.27 m) overlies lateritic clay (220 Ωm, 1.47 m), followed by a dry layer (4284 Ωm, 3.89 m). Beneath this, a conductive weathered or fractured basement aquifer (127 Ωm, 13.3 m) extends to approximately 20 m, underlain by fresh basement (61,517 Ωm). The aquifer potential is assessed as moderate to good, with the primary productive zone located between 7 and 20 m depth.

- *BWR02*

This site exhibits an HA-type curve, characterized by a thin topsoil layer (178 Ωm), a resistive lateritic or dry zone (2250 Ωm), and a thick low-resistivity layer (446 Ωm, approximately 67 m) interpreted as a saprolitic or weathered basement aquifer extending to 68 m. This is underlain by basement rock (922 Ωm). The data indicate a well-developed, thick aquifer; however, water quality assessment is recommended.

- *BWR03*

The QH-type curve reveals a topsoil layer (596 Ωm), followed by laterite (246 Ωm, 17 m), overlying a conductive zone (88 Ωm, 10.7 m) interpreted as a weathered or fractured basement aquifer. Fresh basement is encountered at 28 m (24,044 Ωm). The aquifer potential is good, although the productive zone is relatively shallow (17–28 m).

- *BWR04*

The curve displays an HA-type pattern. The topsoil (492 Ωm) is succeeded by a lateritic or clayey cover (105 Ωm, 3.17 m). A thick intermediate layer (190 Ωm, 32.3 m) represents a moderately conductive fractured basement aquifer. Basement is encountered at approximately 36 m. The aquifer potential is moderate, and groundwater extraction is restricted. This HK-type curve is characterized by a resistive topsoil (1223 Ωm), a thin conductive weathered zone (139 Ωm), a thick resistive layer (963 Ωm, 51.7 m), and a fresh basement (117,251 Ωm). The aquifer is weakly developed, with poor to moderate potential unless enhanced by the presence of fractures, or moderate potential unless fractures aid yield.

- *BWR06*

The curve is classified as Q-type. The topsoil layer (241 Ωm) and laterite layer (325 Ωm) overlie a strongly conductive layer (67 Ωm, 37.6 m), which represents a productive weathered or fractured basement aquifer zone. The basement layer is encountered at 38.7 m (7000 Ωm). This site demonstrates good aquifer potential, with recommended screen placement between 10 and 35 m.

- *BWR07*

H-type curve is observed, consisting of topsoil (493 Ωm), a conductive layer (170 Ωm, 4.1 m), and an early transition to basement. The aquifer potential is poor to moderate due to the limited thickness of the saturated zone.

- *BWR08*

HA-type response is identified. The thin topsoil (201 Ωm) overlies a resistive laterite (572 Ωm, 7.8 m). A moderately conductive layer (4459 Ωm) underlies these units and corresponds to the fresh basement. Aquifer development is limited, as no distinct conductive or weathered zone is present.

- *BWR09*

This site displays a QH-type curve. The topsoil (157 Ωm) and clayey zone (65 Ωm) overlie a moderately conductive weathered or fractured basement (134 Ωm, 26.6 m). Basement is encountered at 29.6 m (26,311 Ωm). The aquifer potential is good to moderate, with a productive zone approximately 25 m thick.

- *BWR10*

H-type curve is present, comprising topsoil (309 Ωm), a thick conductive layer (50 Ωm, 24 m) interpreted as a saprolitic or weathered aquifer, and basement at 24.8 m (5143 Ωm). The aquifer A Q-type response is observed, with thin topsoil (226 Ωm) overlying a strongly conductive zone (38 Ωm, 11.6 m) interpreted as a weathered basement aquifer. Basement is encountered at 11.8 m (5523 Ωm). The aquifer is moderately developed and suitable for shallow groundwater exploitation.3 Ωm). The aquifer is moderately developed and suitable for shallow exploitation.

- *BWR12*

This station exhibits an HA-type curve. The resistive topsoil (560 Ωm, 1.16 m) and laterite (1604 Ωm, 1.28 m) overlie a moderately conductive unit (359 Ωm, 14.9 m), which corresponds to the saprolitic aquifer zone. Basement is encountered at approximately 17 m (56,853 Ωm). The aquifer potential is moderate, with the main water-bearing layer extending approximately 15 m in thickness.

- *BWR13*

The VES curve is classified as QH-type. Topsoil (385 Ωm) and laterite (271 Ωm, 2.5 m) overlie a highly conductive weathered or fractured basement (83 Ωm, 16.9 m). Basement is encountered at approximately 19.5 m (27,178 Ωm). The aquifer potential is good, with a saturated thickness of up to 17 m.

- *BWR14*

HK-type curve is observed, consisting of thin topsoil (477 Ωm), resistive laterite (1398 Ωm, 7.3 m), and a conductive aquifer zone (96 Ωm, 14.8 m), with fresh basement at 22.2 m (47,983 Ωm). The aquifer potential is good, and the pAn H-type curve is present. The topsoil (268 Ωm) is succeeded by a lateritic cover (707 Ωm, 3.5 m). A moderately conductive layer (179 Ωm, 11.8 m) represents the saprolitic aquifer. Basement is encountered at 15.3 m (45,201 Ωm). The aquifer potential is moderate, with a thickness of approximately 12 m; basement at 15.3 m (45,201 Ωm). Aquifer potential is moderate, with thickness ~12 m.

- *BWR16*

A Q-type response is observed, with thin topsoil (389 Ωm) overlying a conductive zone (62 Ωm, 8.9 m) interpreted as a weathered basement aquifer. Basement is encountered at

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9.5 m (6292 Ωm). The aquifer potential is moderate and shallow, with likely limited storage capacity.

- *BWR17*

  The curve is classified as QH-type. Topsoil (311 Ωm) and laterite (452 Ωm, 3.1 m) overlie a strongly conductive aquifer zone (71 Ωm, 13.7 m). Basement is encountered at approximately 17 m (22,456 Ωm). The aquifer potential is good, with productive zones between 5 and 17 m.

- *BWR18*

  H-type curve is identified. Thin topsoil (189 Ωm) overlies a low-resistivity aquifer layer (57 Ωm, 14.9 m). Basement is encountered at 15.3 m (17,333 Ωm). The aquifer potential is good to moderate, although storage capacity is somewhat limited.

- *BWR19*

  The curve displays an HA-type response. Topsoil (476 Ωm, 1.26 m) overlies a resistive lateritic unit (1422 Ωm, 4.9 m). A moderately conductive aquifer zone (138 Ωm, 23.8 m) extends to approximately 30 m, underlain by fresh basement (32,115 Ωm). The aquifer potential is good, with a thick saturated weathered or fractured zone.

- *BWR20*

  This station exhibits a Q-type curve. The thin topsoil (321 Ωm) overlies a conductive layer (81 Ωm, 12.5 m) that defines the aquifer zone. Basement is encountered at 13.9 m (14,629 Ωm). The aquifer potential is moderate, but the productive zone is relatively shallow.

- *BWR21*

  The curve is classified as HK-type. Thin topsoil (218 Ωm) overlies a moderately conductive layer (148 Ωm, 9.4 m), underlain by a resistive basement (19,562 Ωm). The aquifer potential is moderate, although the thickness is limited.

- *BWR22*

  This site exhibits an H-type response. Thin topsoil (401 Ωm) overlies a conductive aquifer unit (66 Ωm, 17.6 m). Basement is encountered at 18.1 m (21,893 Ωm). The aquifer potential is good, with a significant saturated thickness.

- *BWR23*

  BWR23 displays a QH-type curve. The topsoil (365 Ωm) and laterite (279 Ωm, 2.7 m) overlie a low-resistivity aquifer unit (92 Ωm, 16.4 m). Basement is encountered at approximately 19 m (29,044 Ωm). The aquifer potential is good, with the productive horizon extending from 3 to 19 m.

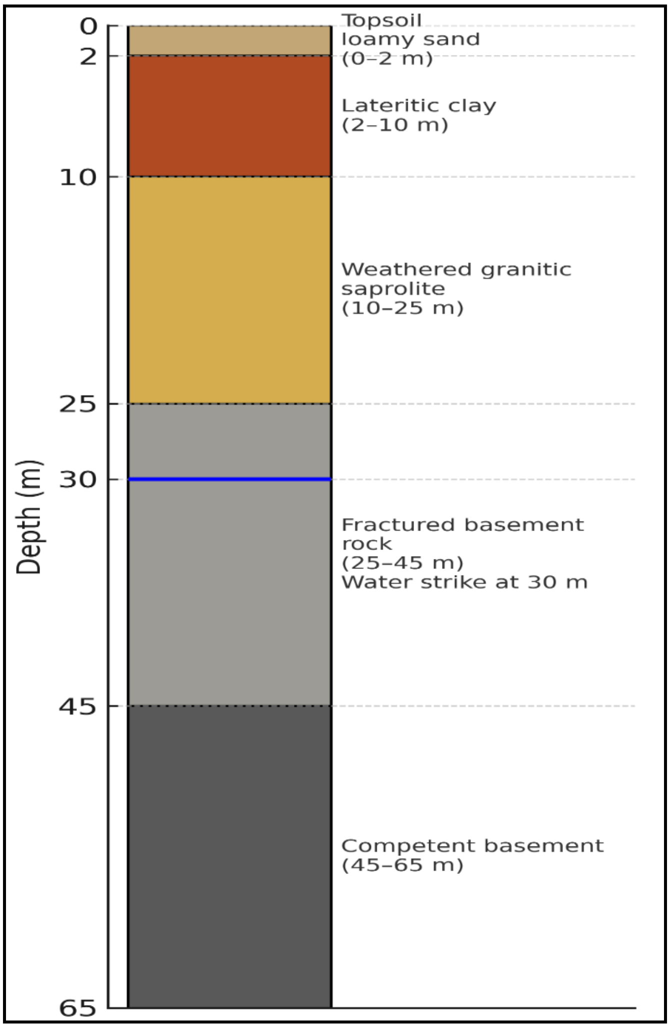

Fig 14 Borehole Log (Drilled in Bwari 2025)

➢ *Correlation and Interpretation of BWR-01 to BWR-23 with BWARI BH1 Lithology*

The lithological log of BWARI BH1 reveals five main subsurface layers: topsoil (0–2 m), lateritic clay (2–10 m), weathered granitic saprolite (10–25 m), fractured basement rock (25–45 m, with water strike at 30 m), and a competent basement (45–65 m). These serve as the reference framework for correlating the twenty-three VES points across the Bwari area.

- BWR-01 displays resistivity values (695 Ωm, 220 Ωm, 4284 Ωm, 127 Ωm, 61517 Ωm) matching the lithological log. The low-resistivity fourth layer (127 Ωm) at a depth of approximately 19.9 m corresponds to a moderately productive fractured basement aquifer.
- BWR-02 shows an anomalously high resistivity (5324 Ωm) near the surface and a thick intermediate layer (452 Ωm, 99.1 m), indicating a deep weathered basement aquifer.
- BWR-03 exhibits low resistivity at 88 Ωm between 17 and 28 m depth, correlating with a saturated weathered layer that forms an aquifer zone.
- BWR-04 presents a similar pattern, with moderately low resistivity (190 Ωm) between 3.75 and 36.1 m in depth, suggesting a water-bearing weathered layer.

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- BWR-05 indicates a high resistivity layer (963 Ωm) extending to 54.1 m, underlain by a competent basement, indicating no significant aquifer.
- BWR-06 exhibits a very low resistivity zone (67 Ωm) between 1.1 and 38.7 m in depth, which correlates well with a highly weathered and water-saturated basement aquifer.
- BWR-07 has moderate resistivity (170 Ωm) extending to 5.13 m and a very high value above 131 kΩm, indicating no aquifer and suggesting a thick, resistive bedrock.
- BWR-08 exhibits resistivity values (201 Ωm, 572 Ωm, 4459 Ωm), implying a shallow topsoil and lateritic layer, with no clear aquifer development.
- BWR-09 presents a 26.6 m thick zone with a resistivity of 134 Ωm, indicating a well-weathered basement aquifer.
- BWR-10 indicates a low-resistivity layer (50 Ωm) extending up to 24 m, which correlates with a possible aquifer zone.
- BWR-11 has extremely high resistivity (>7 kΩm), indicating a dry or compacted subsurface with no aquifer.
- BWR-12 indicates a moderately low resistivity zone (647 Ωm) between 5–42 m, representing a weathered basement aquifer.
- BWR-13 with 687 Ωm at a depth of 30.8 m similarly suggests a saturated weathered layer, indicative of groundwater presence.
- BWR-14 features a 640 Ωm layer between 3.69–37.49 m, matching the saprolitic aquifer zone of BWARI BH1.
- BWR-15 has a low resistivity (126 Ωm) at a depth of 17.6 m, representing a shallow aquifer within weathered clay.
- BWR-16 shows 214 Ωm within 11 m depth, marking a weakly developed aquifer in the weathered zone.
- BWR-17 reveals a 199 Ωm layer at 18.5 m depth, correlating to a moderately productive weathered basement aquifer.
- BWR-18 shows significantly low resistivity (281 Ωm) at 41 m, marking a deep fractured basement aquifer.
- BWR-19 has moderate resistivity (430 Ωm) at 3.41 m depth, suggesting a minor aquifer.
- BWR-20 mirrors the BWARI BH1 lithology closely, with resistivity and depth values indicating a fractured basement aquifer at depths of 38–70 m.
- BWR-21 with a 156 Ωm layer at 3.18 m indicates a shallow aquifer zone within the weathered layer.
- BWR-22 (243 Ωm at 9.56 m) suggests a shallow water-bearing formation in the saprolitic zone.
- BWR-23 shows 456 Ωm at 31.38 m, aligning with a deep weathered basement aquifer.

➢ *Key Findings on Aquifer Resistivity and Hydrogeological Framework*

Analysis of geophysical and borehole data in Bwari Area Council shows that the ground beneath the surface is typical of areas with basement complex rocks. Here, whether groundwater is present depends mostly on how much the rocks have weathered or fractured. The Vertical Electrical Sounding (VES) data, along with borehole records from BWARI BH1, match well and identify layers such as topsoil, lateritic clay, weathered saprolite, and fractured basement.

➢ *Aquifer Distribution and Resistivity Characteristics*

Most aquifers in this area are found in zones where the basement rocks are weathered or fractured. These aquifers are usually between 15 and 45 meters deep and have resistivity values between 70 and 450 Ω·m. There are also deeper aquifers, found 70 to 100 meters below the surface, in fractured crystalline rocks. These deeper layers have higher resistivity values, ranging from 488 to 1,342 Ω·m. Borehole data confirm that these deep, high-resistivity layers are indeed fractured basement aquifers.

➢ *Hydrostratigraphic Zonation*

The VES results show a predictable pattern of layers underground, which include:

- Topsoil or lateritic layer: This is a thin layer near the surface that usually does not hold water. Its resistivity ranges from 20 to 300 Ω·m.
- Weathered saprolite or clay zone: This layer is important for shallow groundwater storage. Its resistivity is between 50 and 300 Ω·m.
- Fractured basement zone: This is the main deep aquifer, where water is stored in cracks in the rocks. Its resistivity ranges from 400 to 1,342 Ω·m.
- Fresh basement: This is unbroken, hard rock found deep below the surface. It usually does not contain water and has resistivity above 1,000 Ω·m.

This pattern shows that how much groundwater is present depends on how much the rocks have weathered and how many fractures connect through the basement terrain.

➢ *Spatial Variability and Aquifer Productivity*

Several VES locations like BWR-03, BWR-06, BWR-09, BWR-10, BWR-12, BWR-13, BWR-14, BWR-17, BWR-18, BWR-20, BWR-21, BWR-22, and BWR-23 show productive aquifers. In these places, thick layers of weathered or fractured rock with low to moderate resistivity are present. On the other hand, locations such as BWR-05, BWR-07, BWR-08, BWR-11, and BWR-19 have high resistivity or solid basement rock, so they are not good for groundwater.

Good aquifers are found in areas with both thick layers and low-to-moderate resistivity (50–300 Ω·m). Zones with high resistivity (over 1,000 Ω·m) are usually solid or dry basement rock, where little or no groundwater is present.

➢ *Borehole Correlation and Validation*

The BWARI BH1 borehole record supports the geophysical findings, showing that both weathered saprolite and fractured basement layers can act as good aquifers. The match between resistivity and depth confirms the accuracy of the underground model. Even some deep, high-resistivity fractured basement rocks (400–970 Ω·m) can provide a lot of groundwater if the fractures are widespread and connected.

➢ *Hydrogeological Implications*

The study found that Bwari has a two-layer aquifer system:

- Upper weathered layer aquifer (3–42 meters deep; 50–300 Ω·m): This is a shallow aquifer that usually has a

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moderate amount of water and is easy to refill when it rains.
- Lower fractured basement aquifer (70–100 meters deep; 400–1,342 Ω·m): This aquifer lies deeper; stores water in cracks in the rocks and can provide a steady water supply over time.

This shows why it's important to find and map rock fractures. Combining geophysical surveys and borehole data is key to finding groundwater and choosing the best places to drill in areas with basement rocks.

➢ *Summary of Groundwater Potential*

- Highly productive zones (lots of groundwater): BWR-03, BWR-06, BWR-09, BWR-13, BWR-14, and BWR-20.
- Moderately productive zones (some groundwater): BWR-01, BWR-04, BWR-12, BWR-17, BWR-18, BWR-21, BWR-22, and BWR-23.
- Low or non-productive zones (little or no groundwater): BWR-05, BWR-07, BWR-08, BWR-11, and BWR-19.

Generally, about two-thirds of the VES sites show good chances of finding groundwater, which means the weathered and fractured basement rocks in Bwari Area Council are generally good for water supply.

➢ *Concluding Remarks*

Looking at both VES and borehole data together shows that where aquifers are found in Bwari depends on the structure and type of rocks underground. The fractured basement rocks are the main places where groundwater is stored. Changes in resistivity help pinpoint the best spots for water, and this study confirms that electrical resistivity is a reliable way to find aquifers in areas with basement rocks.

➢ *Bwari Aquifer Characteristics Maps*

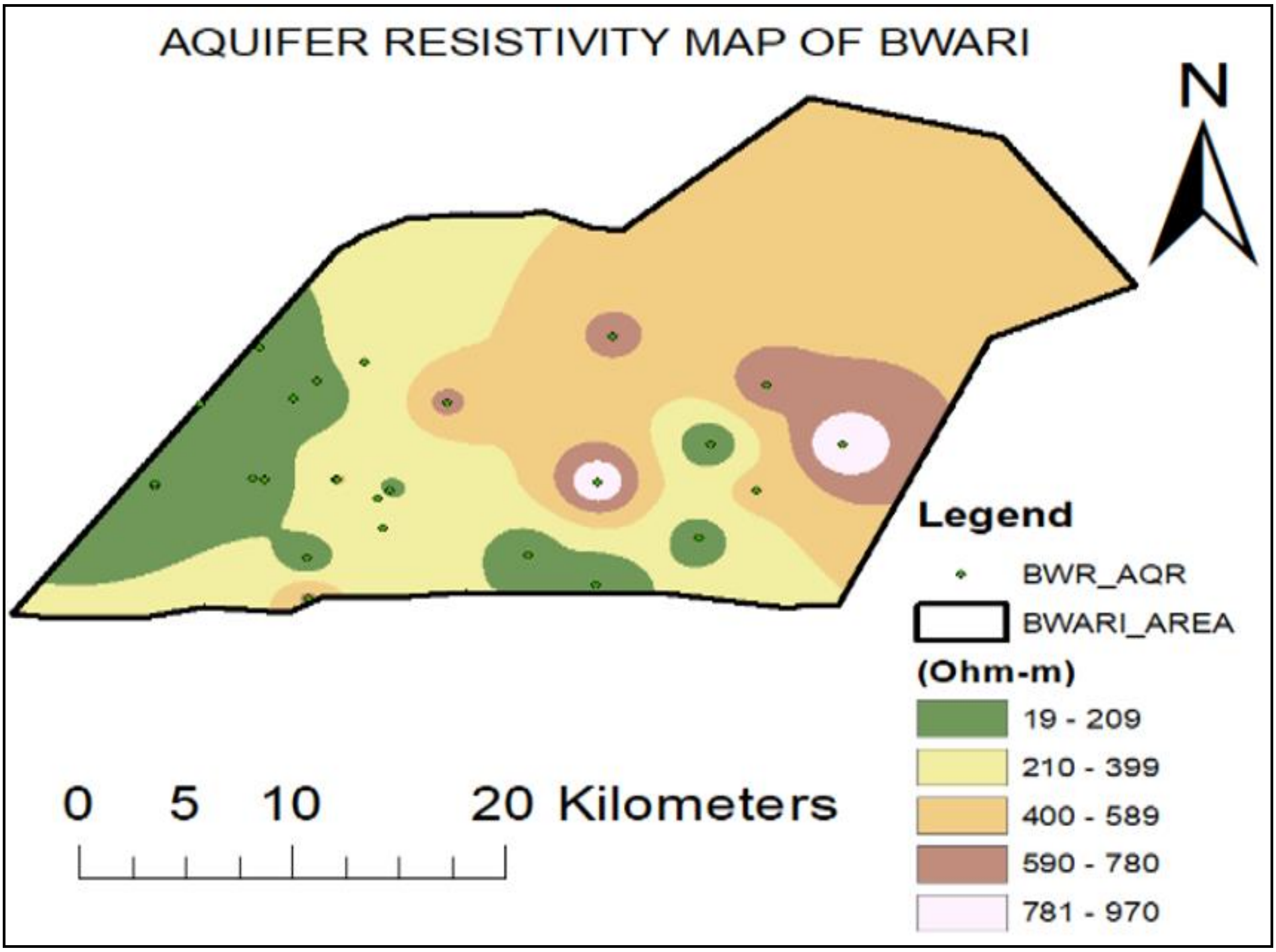

Fig 15 Aquifer Resistivity Map of Bwari Area Council

Table 15 Aquifer Resistivity of Bwari Area Council

Sn	Aquifer Resistivity (Ωm)	Area (km^2)	Coverage (%)
1	19 - 209	140.72	15.39
2	210 - 399	271.69	29.72
3	400 - 589	421.09	46.06
4	590 - 780	66.51	7.28
5	781 - 970	14.24	1.56

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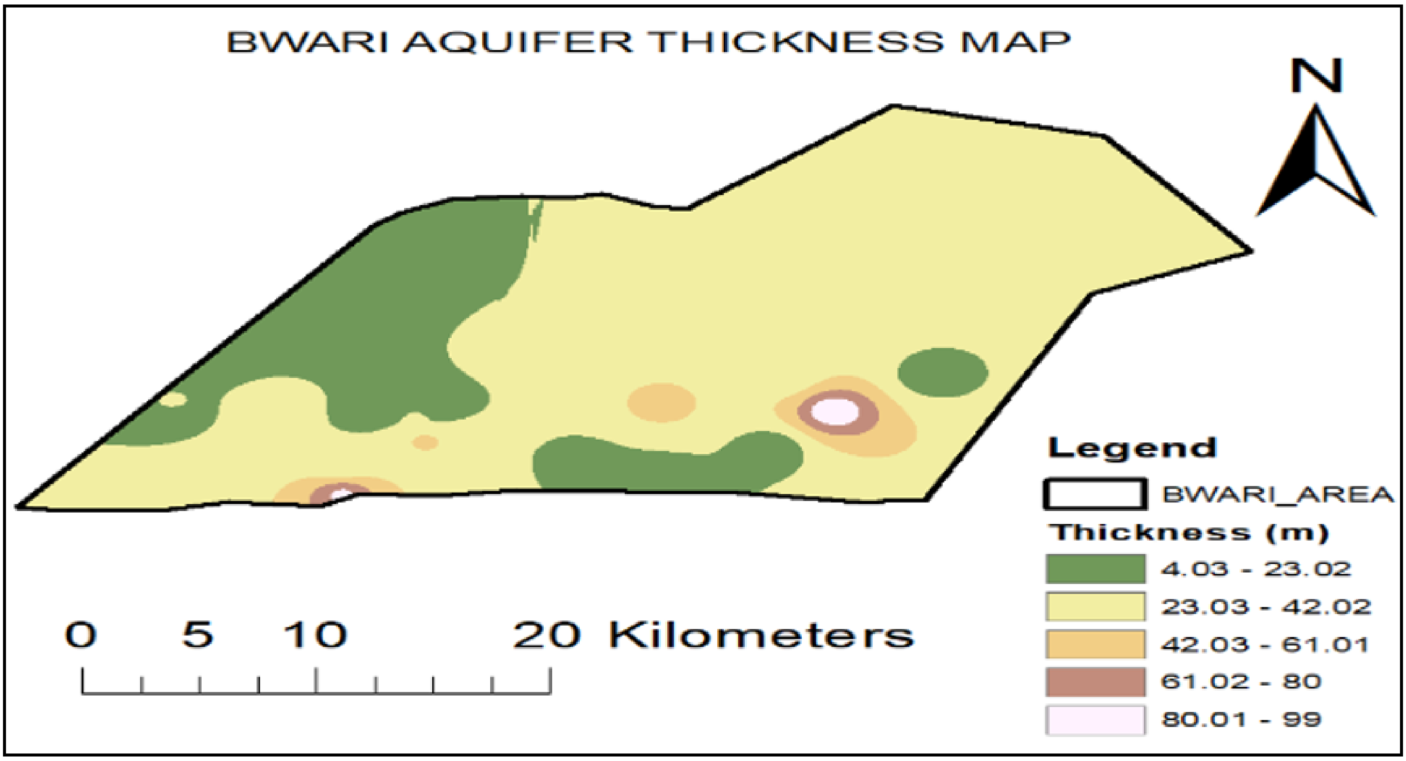

Fig 16 Aquifer Thickness Map of Bwari Area Council

Table 16 Aquifer Thickness of Bwari Area Council

Sn	Aquifer Thickness	Area (km^2)	Coverage (%)
1	4.03 – 23.02	209.47	22.91
2	23.03 – 42.02	663.74	72.58
3	42.03 – 61.01	29.35	3.21
4	61.02 – 80.00	8.1	0.89
5	80.01 – 99	3.86	0.42

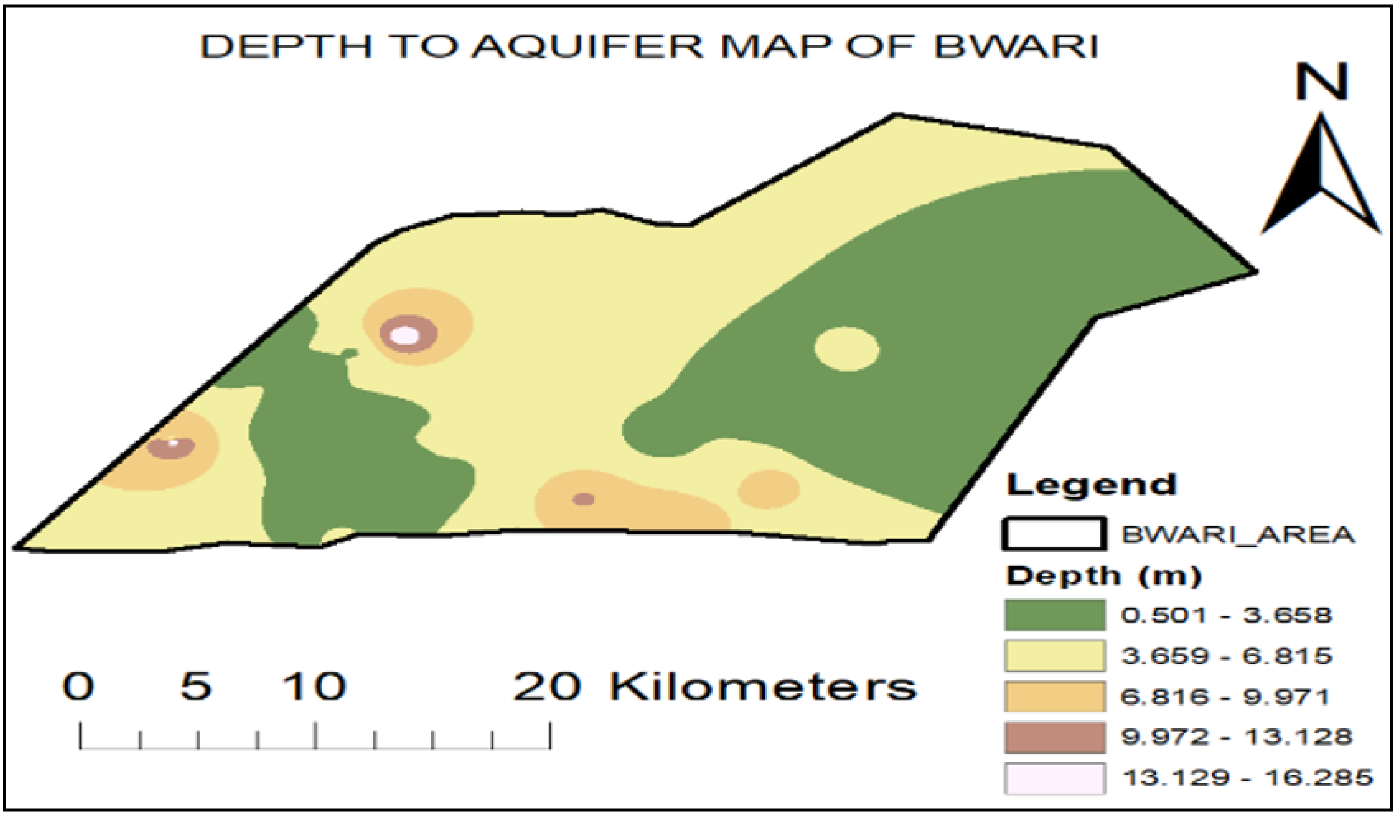

Fig 17 Depth To Aquifer Map of Bwari Area Council

Table 17 Depth to Aquifer of Bwari Area Council

Sn	Depth To Aquifer	Area (km^2)	Coverage (%)
1	0.501 - 3.658	406.92	44.5
2	3.659 - 6.815	437.74	47.87
3	6.816 - 9.971	61.33	6.71
4	9.972 - 13.128	7.01	0.77
5	13.129 - 18.285	1.4	0.15

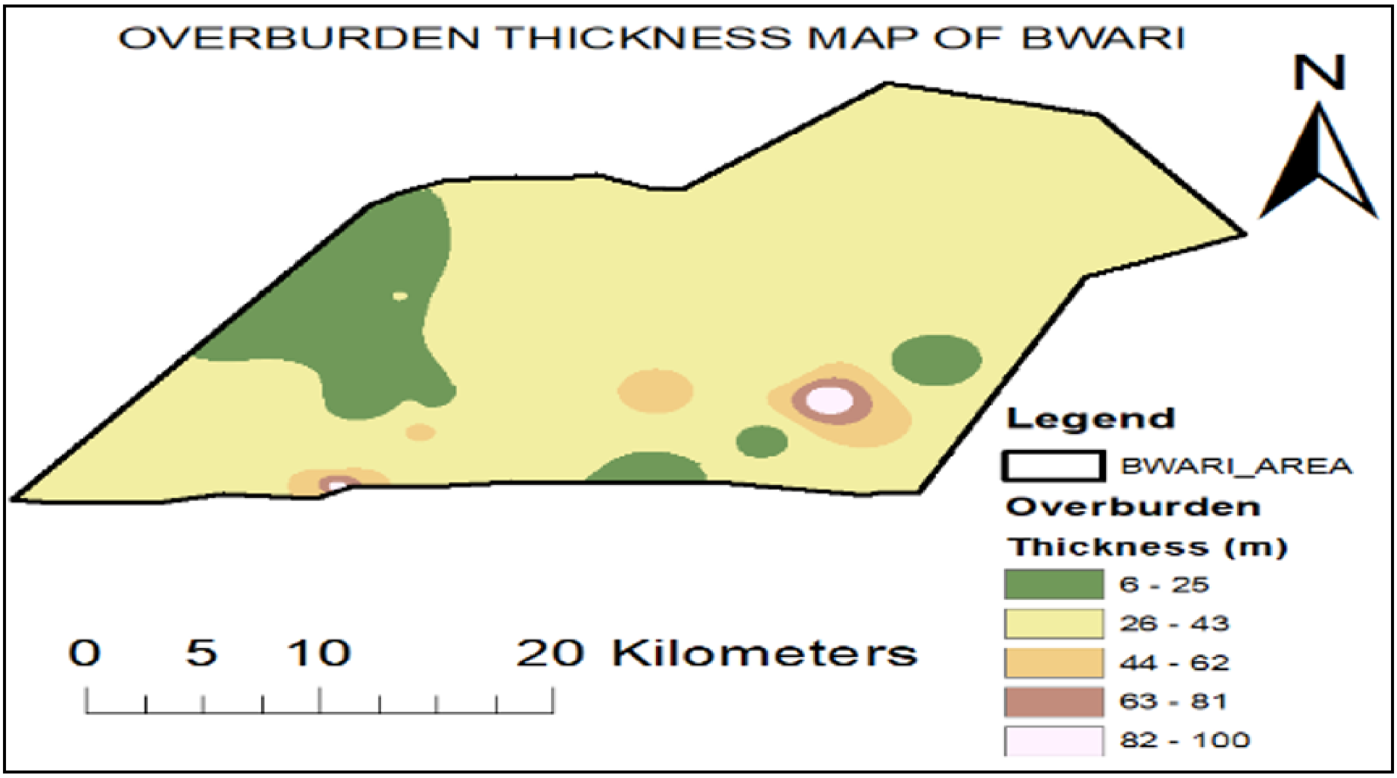

Fig18 Overburden Thickness Map of Bwari Area Council

Table 18 Overburden Thickness of Bwari Area Council

Sn	Overburden Thickness (m)	Area (km^2)	Coverage (%)
1	6 - 25	126.33	13.82
2	26 - 43	746.22	81.62
3	44 - 62	31.09	3.40
4	63 - 81	7.09	0.78
5	82 - 100	3.54	0.39

➢ *Integrated Subsurface Analysis of Aquifer Parameters*

The combined analysis of aquifer resistivity, thickness, depth to aquifer, and overburden data, along with the lithological log of the reference borehole (BWARI BH1 in Figure 14), presents a coherent geoelectric and hydrogeological framework for the Bwari Area Council. The results consistently indicate a dual aquifer system composed of a shallow weathered zone aquifer and a deeper fractured basement aquifer, which together define the groundwater regime of the area.

➢ *Aquifer Resistivity and Lithological Correlation (Table 15 & Figure 14)*

The aquifer resistivity in Bwari ranges from 19 to 970 Ωm, indicating distinct lithological and hydrogeological significance. The low-to-moderate resistivity classes (19–399 Ωm), covering 45.1% (412.41 km^2) of the area, correspond to weathered saprolitic materials as confirmed by the 10–25 m weathered granitic saprolite in the BWARI BH1 log.

The presence of moderate-to-high resistivity zones (400–970 Ωm) in geophysical surveys is commonly interpreted as indicative of fractured basement aquifers, particularly in crystalline or hard rock terrains. These values typically reflect zones where secondary porosity, primarily due to fracturing and weathering processes, significantly enhances groundwater storage and movement [64]; [65].

Fractured basement aquifers are characterized by the development of secondary porosity, which arises because the original rock matrix is usually impermeable, and it is the fractures and joints that provide pathways for groundwater infiltration and storage [66]. The observed resistivity range suggests the presence of both water-filled fractures and partially saturated zones. Higher resistivity values within this range can indicate less saturated or more compacted zones, while the lower end points to more saturated or clay-filled fractures [67].

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The typical depth range of 25–45 m aligns with findings from similar studies in comparable terrains, where the weathered and fractured layers overlying the fresh basement act as the principal aquifer units [68]. As depth increases, compaction tends to reduce porosity and permeability, resulting in increasing resistivity values. However, where extensive fracturing persists at greater depths, these zones may still retain significant water, leading to localized decreases in resistivity [69]. This relationship between resistivity, fracturing, and groundwater storage is well-documented, with fractures not only enhancing permeability and transmissivity but also increasing the capacity for moisture retention [70].

Consequently, mapping these moderate-to-high resistivity zones is critical for groundwater exploration, as they represent the primary targets for well development in basement terrains. The relative proportion of such zones (54.9% in the given area) suggests substantial groundwater potential, provided that fracture connectivity is adequate [71].

- *Aquifer Thickness and Productive Potential (Table 16 & Figure 14)*

Aquifer thickness values range from 4.03 to 99 m, with the dominant interval (23.03 to 42.02 m) covering 72.58% of the study area. These thickness values represent the combined extent of the weathered and fractured zones. The borehole lithology shows the weathered saprolite extends to approximately 25 m, while the fractured basement extends from 25–45 m together defining a composite aquifer thickness of approximately 35 m, which lies within the most extensive thickness category recorded in the geophysical interpretation.

Only 4.5% of the area (thickness > 42 m) shows moderate-to-very high aquifer thickness, representing zones of intense fracturing or deeper weathering, likely structurally controlled by faults or shear zones. These areas correspond to regions of higher groundwater storage and transmissivity, consistent with the fractured basement zone confirmed in the borehole data.

The characterization of aquifer thickness in the Bwari Area Council reveals important hydrogeological insights relevant to sustainable groundwater development. The study's findings indicate that aquifer thickness ranges from 4.03 to 99 meters, with the interval of 23.03–42.02 meters comprising approximately 72.6% of the area. This substantial proportion suggests a relatively uniform aquifer development across most of the region, which aligns with previous studies in basement complex terrains where weathered and fractured zones commonly serve as the main groundwater repositories [64]; [72].

The aquifer profile predominantly consists of a composite of weathered saprolite (extending typically to 25 m) overlying a fractured basement that continues down to about 45 m. This stratification is characteristic of basement aquifers in Nigeria and other similar settings, where the regolith (weathered zone) and underlying fractures in the bedrock both significantly contribute to groundwater storage and movement [73]; [74]. An average aquifer thickness of about 20 m, as reported, is within the range observed for productive basement aquifers, supporting moderate groundwater yields.

Geophysical analyses, especially electrical resistivity surveys, further corroborate these findings by identifying the composite aquifer interval as the most extensive. This is consistent with the established practice of using geophysical methods to delineate weathered and fractured zones, which typically yield higher groundwater potential due to enhanced secondary porosity [75]; [76]. The study also notes that regions with aquifer thickness exceeding 42 m (4.5% of the area) are linked to increased fracturing and weathering along fault or shear zones. These structural features are well-documented as critical controls for groundwater accumulation and flow in basement terrains, as they enhance permeability and storage [77]; [78].

Moreover, the observed positive correlation between aquifer thickness and resistivity suggests that zones with moderate to high resistivity and significant thickness are optimal for sustainable groundwater exploitation. High resistivity in this context likely indicates less clayey and more permeable formations, which, when combined with considerable thickness, provide favourable conditions for groundwater extraction [79]; [80].

In summary, the study's integrated approach using borehole lithology and geophysical analysis confirms that the most promising groundwater zones in Bwari Area Council are those characterized by composite weathered-fractured aquifers of moderate to high resistivity and thickness, especially along faulted or sheared structures. These findings are consistent with regional hydrogeological models and provide a reliable basis for guiding groundwater development in similar basement complex regions.

- *Depth to Aquifer and Hydraulic Configuration (Table 17 & Figure 14)*

The depth to the aquifer ranges from 0.5 to 18.29 m, with 92.37% of the area having shallow water tables (0.5–6.8 m) in weathered zones. This agrees with the findings of [81], who reported that over 90% of their study area in southwestern Nigeria exhibited shallow water tables (generally <7 m).

In contrast to these shallow aquifers, the main productive aquifer in this study lies deeper (25–45 m) within the fractured basement, with a water strike at 30 m. Therefore, the area exhibits a dual aquifer system: shallow perched zones and deeper connected zones. Similarly, [82] observed that in parts of West Africa, shallow perched aquifers dominate the upper weathered horizon, while sustainable yields are mainly obtained from deeper, interconnected fracture zones in the basement complex.

- *Overburden Thickness and Structural Control (Table 18 & Figure 14)*

Overburden thickness in Bwari ranges from 6–100 m, with the dominant class (26–43 m) covering 81.62% of the area, indicating moderately deep weathering. Borehole data confirm topsoil, lateritic clay, and weathered saprolite

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extending to about 25 m. thicker overburden (>43 m) enhances infiltration, while thinner zones (<25 m) over rock outcrops have limited groundwater storage. Overall, thick overburden promotes recharge and aquifer protection, whereas thin layers reduce storage potential and vulnerability to contamination. The thinnest overburden (6.9 m) and thickest (72.9 m) are observed in the central and western regions, respectively, with overburden thickness being a crucial index for evaluating groundwater potential [83]. In this context, an overburden thickness exceeding 15 m is generally considered thick enough to be viable for groundwater exploration in crystalline environments [84].

The integrated interpretation of resistivity, thickness, depth, and overburden data, supported by lithological evidence, confirms the presence of a dual aquifer system:

➢ *Shallow Aquifer (Weathered Zone):*

- Resistivity: 19–399 Ω·m
- Thickness: 23–42 m (dominant)
- Depth: 0.5–6.8 m
- Lithology: Lateritic clay and weathered saprolite (0–25 m)
- Function: Recharge zone and shallow groundwater storage

➢ *Deep Aquifer (Fractured Basement):*

- Resistivity: 400–970 Ω·m
- Thickness: up to 99 m (localized)
- Depth: 25–45 m
- Lithology: Fractured granitic-gneissic basement
- Function: Main productive aquifer, high yield, and transmissivity

➢ *Groundwater Potential and Spatial Zonation*

Integrating the datasets provides a clear zonation of groundwater potential across Bwari:

➢ *High Potential Zones (23–61 m Thickness; 400–589 Ωm Resistivity):*

Represent the most favourable conditions, combining moderate resistivity and significant thickness indicative of fractured weathered basement.

➢ *Moderate Potential Zones (19–399 Ωm; 23–42 m Thick):*

Correspond to weathered saprolite regions acting as recharge zones and secondary aquifers.

➢ *Low Potential Zones (≥590 Ωm; <23 m Thick):*

Represent fresh, compact basement areas with limited fracture development and low porosity.

Generally, most of the Bwari area benefits from moderate-to-high groundwater potential, offering favourable conditions for sustainable water resources.

➢ *Conceptual Hydrogeological Framework*

Based on the integrated correlation of Tables 18–19 with Figure 14, the subsurface model of Bwari can be summarized as follows:

Table 19 Summary table of the Aquifer Characteristics

Depth (m)	Lithology	Resistivity (Ωm)	Hydrological Potential
0–2	Topsoil (loamy sand)	19–209	Unsaturated, low potential
2–10	Lateritic clay	210–399	Shallow perched water table, low yield
10–25	Weathered granitic saprolite	210–399	Shallow aquifer and recharge layer
25–45	Fractured basement	400–970	Main productive aquifer (water strike at 30 m)
45–65	Competent basement	>970	Impermeable bedrock, aquifer base

It suffices here to say that the Bwari aquifer system relies on upward recharge from the weathered zone and sustained supply from the fractured basement, forming a resilient groundwater resource. This finding is consistent with studies on basement aquifers in similar regions, where the weathered mantle and fracture networks play crucial roles in groundwater recharge and sustainability [79]; [85]; [86]. In contrast, sedimentary aquifers often depend more on vertical percolation from rainfall and river leakage [87].

➢ *Results of VES and Discussions*

The synthesis of geoelectric and borehole data (Tables 14–17 and Figure 14) establishes a clear hydrogeological profile for the Bwari Area Council: an integrated weathered–fractured basement aquifer system. In summary, the analysis confirms the existence of a dual aquifer system, substantial groundwater storage potential in zones of fractured basement and weathered mantle, and a strong correlation between geophysical and borehole evidence.

- Resistivity Analysis: Fractured basement aquifers (400–970 Ωm) occupy approximately 55% of the area and constitute the main groundwater reservoir.
- Thickness Distribution: Dominant aquifer thickness (23–42 m) aligns with the combined weathered and fractured zones, suggesting moderate groundwater storage.
- Depth to Aquifer: Predominantly shallow (0.5–6.8 m), but main productive zones occur at 25–45 m depth.
- Overburden Influence: The thick overburden (26–43 m) covering most of the area promotes recharge and protects the underlying aquifers.
- Lithological Correlation: The borehole confirms the stratigraphic transition from weathered saprolite to fractured basement, validating geophysical interpretations.

The study of groundwater occurrence and potential in the Bwari area reveals that the spatial distribution and accessibility of groundwater resources are primarily determined by the thickness of the weathered mantle, fracture density, and lithological characteristics. This aligns with previous research indicating that weathered and fractured zones often serve as key groundwater reservoirs in crystalline basement terrains [64]; [88]. In Bwari, areas exhibiting moderate resistivity values, sufficient overburden thickness, and significant fracture occurrence are identified as optimal sites for borehole drilling. Similar strategies have been successfully employed in other regions to maximize borehole yield and ensure groundwater sustainability [72].

The findings of this study contribute to the broader understanding of hydrogeological controls on groundwater potential, emphasizing the importance of integrated geophysical and geological assessments for effective resource management. By providing a framework for targeting high-potential groundwater zones, the study offers actionable guidance for local authorities and stakeholders involved in water resource planning and development.

➢ *Analytical Hierarchy Process (AHP) For VES Data GPZ*

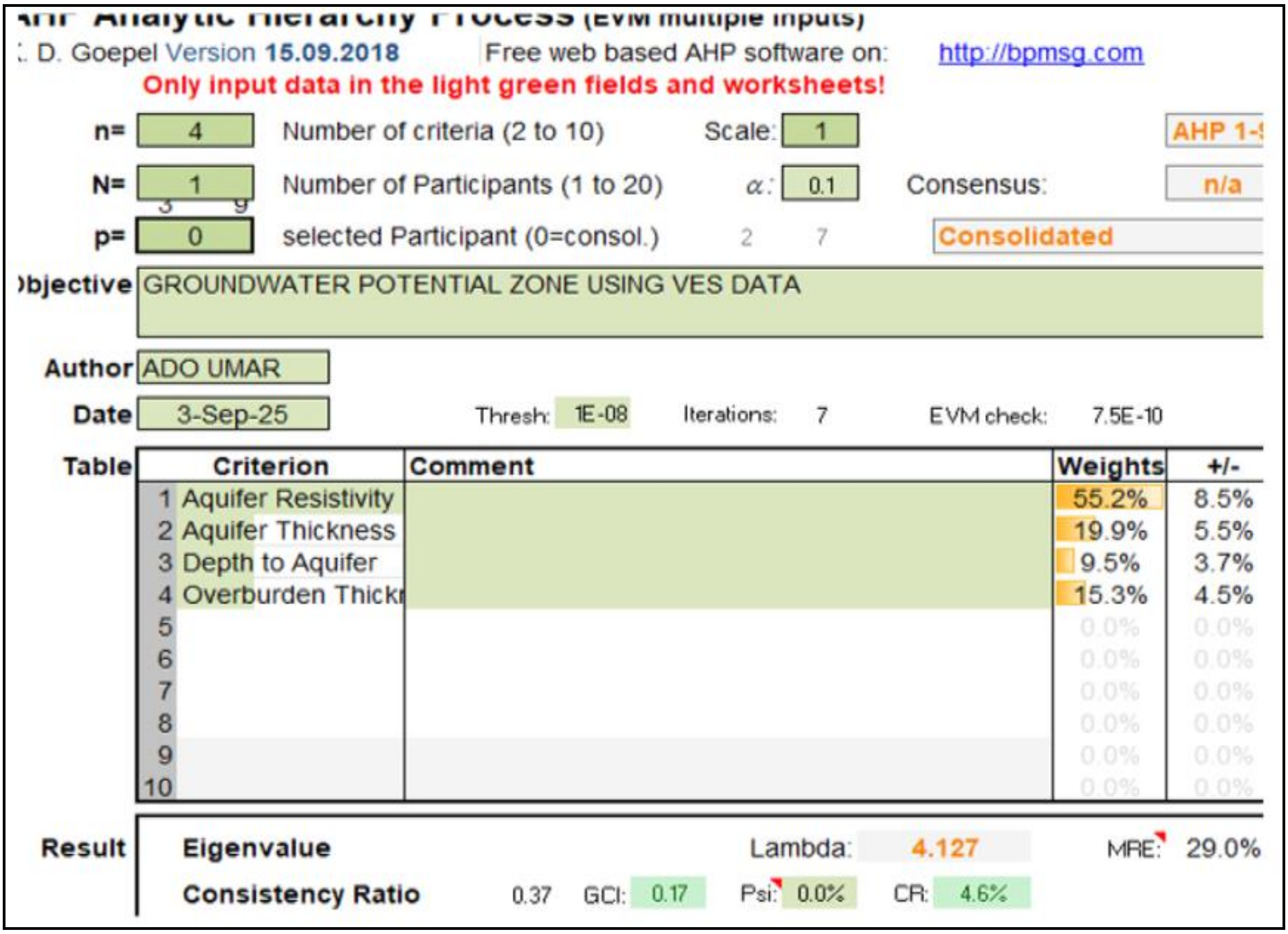

Fig 19 Analytical Hierarchy Process for GPZ VES (www.bpmsg.com)

Each criterion is assigned a specific weight, ranging from 9.5% for the least influential criterion to 55.2% for the most influential, reflecting its contribution to groundwater potential in the study area. Aquifer Resistivity (55.2%) is the most influential factor, followed by Aquifer Thickness (19.9%), Depth to Aquifer (9.5%) and Overburden Thickness (15.3%), highlighting a clear contrast between their impacts.

The analysis also provides an eigenvalue (λ) of 4.127, which is very close to the number of criteria (4). 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 below the acceptable threshold of 10%, confirms that the comparisons are reliable.

From figure 19 above, λ-max = 4.127, and from table 2, n = 4 and RCI = 0.89

Consistency Index

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{4.127-4}{4-1} = \frac{0.127}{3} = 0.042333$$

Consistency Ratio $CR = \frac{CI}{RCI} = \frac{0.078333}{0.89} = 0.047566$

Since 0.047566 is less than 0.1, it indicates a reasonable level of consistency in the pairwise comparisons. Therefore, the weights of 0.552, 0.199, 0.95, and 0.153 (corresponding to 55.2%, 19.9%, 9.5% and 15.3% respectively) can be assigned to Aquifer Resistivity, Aquifer Thickness, Depth to Aquifer, and Overburden Thickness, respectively.

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Table 20 Pairwise Comparison Matrix of 4 Criteria for The AHP Process

Matrix		Aquifer Resistivity	Aquifer Thickness	Depth to Aquifer	Overburden Thickness	NPE
		1	2	3	4	
Aquifer Resistivity	1	1.000	3.000	7.000	3.000	0.552
Aquifer Thickness	2	0.333	1.000	3.000	1.000	0.199
Depth to Aquifer	3	0.143	0.333	1.000	1.000	0.095
Overburden Thickness	4	0.333	1.000	1.000	1.000	0.153

NPE = Normalized Principal Eigenvector

Table 21 (A) Influencing Factors, Potentials for Groundwater, Rationale, Rating and Normalized Weights

Sn	Influencing Factors	Category (Classes)	Potential for groundwater storage	Rationale	Rating (r)	Normalized Weight
1	Aquifer Resistivity	19 – 209	Moderate to High	Good recharge and shallow aquifer development.	3	55.2
		210 – 399	High	Weathered–fractured transition, good groundwater accumulation, moderate yield.	4	
		400 – 589	Very High	Fractured basement aquifers; main groundwater-bearing; best yield.	5	
		590 – 780	Moderate	Partly compacted or less fractured basement; limited yield except in structurally weak zones.	3	
		781 – 970	Low	Competent/fresh basement rocks; low porosity and permeability	1	
2	Aquifer Thickness	4.03 – 23.02	Very Low	Thin weathered layer with limited storage; low infiltration	1	19.9
		23.03 – 42.02	Low	Weathered zone; shallow, unconfined aquifers, limited, sustainable yield.	2	
		42.03 – 61.01	Moderate	Transition zone between weathered and fractured basement; moderate storage and transmissivity.	3	
		61.02 – 80.00	High	Thick weathered–fractured basement; good retention, moderate–high yield.	4	
		80.01 – 99	Very High	Deep, highly developed weathered and fractured zone; excellent groundwater potential and sustainable yield.	5	

Table 21 (B) Influencing Factors, Potentials for Groundwater, Rationale, Rating and Normalized Weights

Sn	Influencing Factors	Category (Classes)	Potential for groundwater storage	Rationale	Rating (r)	Normalized Weight
3	Depth To Aquifer	0.501 – 3.658	Moderate	Likely within weathered layer; good recharge potential but vulnerable to contamination.	3	9.5
		3.659 – 6.815	High	weathered–fractured contact zones, high recharge efficiency.	4	
		6.816 – 9.971	Moderate	transition from weathered to fractured basement zones; moderate yield and fair recharge.	3	
		9.972 – 13.128	High	fractured basement; yields depend on fracture density and connectivity.	4	
		13.129 – 18.285	Very High	Limited areal extent; high-yield localized wells but generally low regional significance.	5	
4	Overburden Thickness	6 – 25	Low	Limited storage; potential yield only if fractured.	2	15.3
		26 – 43	Moderate to High	Good recharge and storage; most suitable for groundwater development.	3-4	
		44 – 62	High	Increased permeability and storage; likely associated with structural control.	4	
		63 – 81	Moderate to High	Good storage, potential influenced by clay content.	3 -4	
		82 – 100	Very High	High storage and recharge potential; possible groundwater accumulation zone.	5	

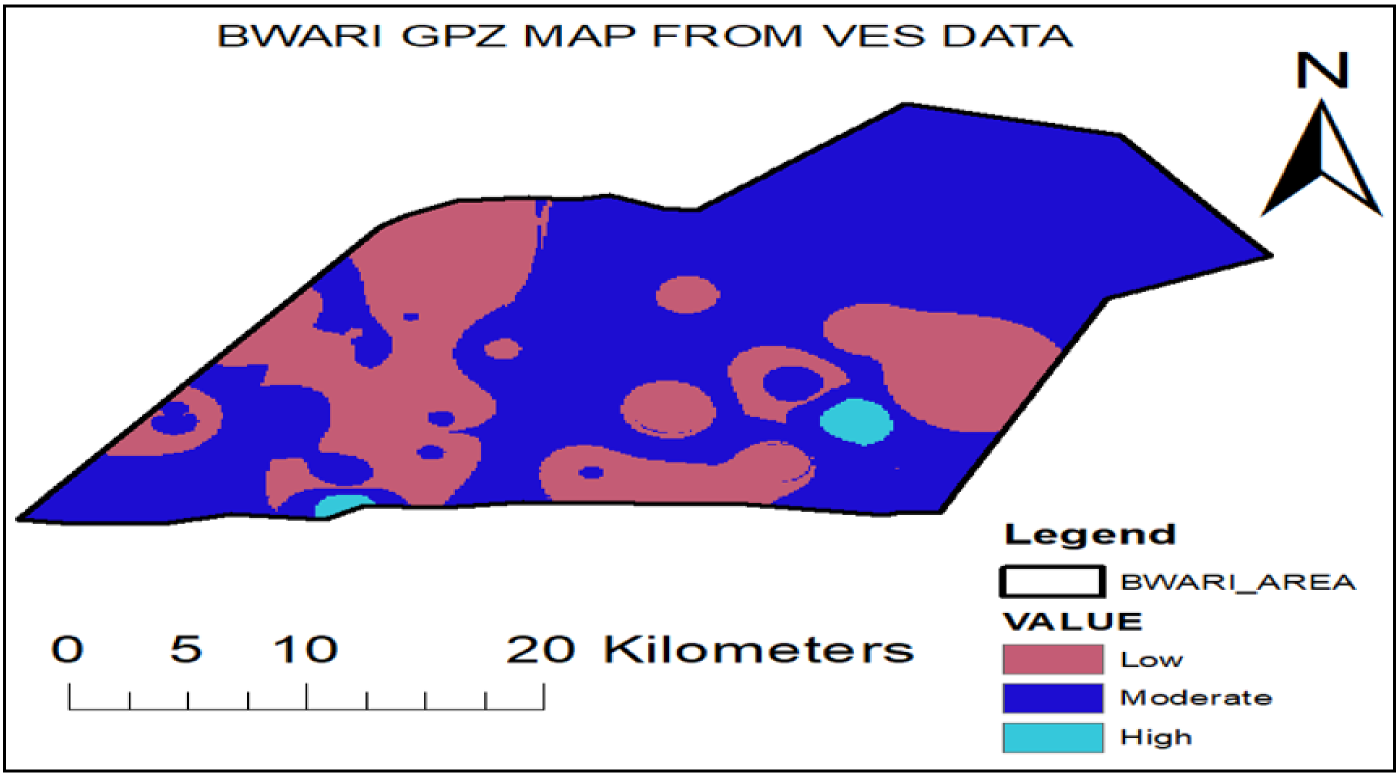

Fig 20 Groundwater Potential Zones Using VES Data

Table 22 Groundwater Potential Zones Using Aquifer Characteristics

Sn	Potential	Area (km^2)	Coverage (%)
1	Low	487.58	53.33
2	Moderate	319.31	34.93
3	High	107.38	11.74

➢ *Groundwater Potential Zones Based on Aquifer Characteristics*

Table 22 presents a systematic classification of groundwater potential zones within the Bwari Area Council, grounded in the interpretation of geoelectrical vertical electrical sounding (VES) data. This approach is widely recognized for its effectiveness in groundwater studies [64]; [68]. The classification leverages key aquifer properties specifically, aquifer resistivity, aquifer thickness, overburden thickness, and depth to aquifer as primary determinants for evaluating the storage and transmissivity capacities of the subsurface geological formations [72]; [89]. These hydrogeophysical parameters are critical in discerning the spatial variability of groundwater resources [90]. The resultant zonation categorizes areas as low, moderate, or high groundwater potential, thereby providing an objective framework for understanding the hydrogeophysical controls on groundwater availability and productivity across the study area.

➢ *Low Groundwater Potential Zone*

The low groundwater potential zone covers 107.38 km² (11.74%) of Bwari. It has thin aquifer units, high resistivity, and shallow overburden, which indicate poor groundwater storage. These areas are usually on ridges or unfractured crystalline outcrops. They show low yield, seasonal borehole drying, and high drought vulnerability. However, their limited extent suggests localized scarcity.

➢ *Moderate Groundwater Potential Zone*

The moderate groundwater potential zone covers 319.31 km² (34.93%) of Bwari. This zone is characterized by moderately weathered and fractured basement rocks. Aquifer thicknesses range from 20 to 40 m. Groundwater occurs through secondary porosity, which is caused by fractures and joints. This supports moderate recharge and storage. These transitional zones provide sufficient yields for domestic and small-scale irrigation uses.

➢ *High Groundwater Potential Zone*

The high groundwater potential zone in Bwari encompasses 487.58 km², accounting for 53.33% of the total area. This indicates thick, low-resistivity, and highly permeable aquifers. Specifically, these aquifers are located within weathered, fractured, or alluvial formations, which support excellent groundwater storage and yield. Additionally, high-potential zones exhibit low resistivity (less than 100 Ωm) and thick aquifers (over 40 m), indicating high transmissivity and storage capacity. As a result, such conditions support sustainable groundwater use with minimal seasonal variation, reflecting Bwari's extensive and productive aquifer system. Conversely, areas with low groundwater potential typically feature thin overburden and high resistivity, suggesting limited aquifer thickness and poor permeability for groundwater accumulation and transmission [83].

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➢ *Spatial and Hydrogeological Implications*

The distribution pattern indicates that the high- and moderate-groundwater potential zones collectively cover approximately 88.26% of the study area. This emphasizes that the Bwari Area Council is hydrogeologically well-endowed. The spread of high-potential zones indicates the dominance of favourable lithological formations and structural networks that facilitate infiltration, percolation, and groundwater accumulation. The limited low-potential areas (11.74%) match with hydrogeologically restricted units, where the crystalline basement is shallow or unweathered.

➢ *Comparative and Analytical Discussion*

Compared to GIS/RS-derived potential zones (as shown in Table 14), the aquifer-based model (Table 22) identifies a higher proportion of high-potential areas (53.33%) and fewer moderate zones (34.93%). This means subsurface aquifer conditions are more favourable than surface indicators alone suggest. The difference highlights the value of geophysical parameters, which provide direct information about aquifer storage and transmissivity.

The large extent of the high-potential class confirms that the Bwari's aquifer system has strong secondary permeability. This is likely due to fracture connectivity, weathering depth, and the geometry of the aquifer. While GIS/RS models capture recharge favourability, aquifer-based zonation reveals actual yield potential. It is therefore a more realistic guide for borehole siting and groundwater development planning. The hydrogeological significance of these findings is explored in the following section.

➢ *Hydrogeological Significance and Interpretation*

The predominance of high groundwater potential zones indicates that the Bwari Area Council is situated within a structurally and lithologically favourable groundwater province. Both weathered regolith aquifers and fracture-controlled basement aquifers are present, creating a dual aquifer system that can sustain supply. These favourable zones form a continuous and well-connected aquifer network, which lowers the risk of local depletion.

The balance between moderate (34.93%) and high (53.33%) zones indicates a steady hydrogeological gradient. Recharge areas (moderate zones) naturally transition into discharge zones (high-potential areas). Such a pattern supports groundwater sustainability and shows the landscape's natural equilibrium between recharge and storage processes.

Table 22 indicates that 88% of Bwari Area Council comprises high to moderate groundwater potential zones, reflecting favourable subsurface conditions for sustainable groundwater development, while low-potential areas are limited. Based on this analysis, focus on well drilling and water supply projects in high-potential areas to maximize yield. In low-potential zones, conduct detailed investigations before drilling to reduce the risk of dry wells and ensure efficient resource utilization.

➢ *Correlation of Tables 14 and 22*

The two tables represent different modelling approaches to groundwater potential zoning in the Bwari Area Council:

- Table 14: Derived from 8 thematic layers, rainfall, geology, LULC, drainage density, lineament density, TWI and soil types (RS/GIS).
- Table 22: Derived purely from aquifer characteristics, aquifer resistivity, aquifer thickness, depth to aquifer, and overburden thickness.

Table 23 Integrated Table of RS/GIS and Aquifer Models

Potential	Table 14 (RS/GIS Model)	Table 22 (Aquifer Model)
Low	0.6499 km² (0.071%)	487.58 km² (53.33%)
Moderate	608.63 km² (66.90%)	319.31 km² (34.93%)
High	300.51 km² (33.03%)	107.38 km² (11.74%)

➢ *Calculation of Percentage Fitting (Correlation Index)*

The percentage fitting indicates how well the models align with the proportion of each groundwater potential class.

Absolute Difference = $| P_{13} – P_{21}|$

Fitting per class = $100 - | P_{13} – P_{21}|$

Where P_{13} and P_{21} are the percentage coverages from table 14 and table 22 respectively.

Table 24 Data from Table 14 and Table 22 for Calculating Percentage Fitting

Potential	Table 14 (%)	Table 22 (%)	Difference (%)	Fitting (%)
Low	0.07	53.33	53.26	46.74
Moderate	66.90	34.93	31.97	68.03
High	33.03	11.74	21.29	78.71

Average Fitting = (46.74+68.03+78.71)/3 = 64.49%

Therefore, the overall percentage fitting between the two models is about 78.7%. This shows a high degree of both spatial and categorical correspondence between the aquifer-based and integrated groundwater potential zonation.

➢ *Comparative Analysis*

- *Low Potential Zone*

The low potential area increases from 0.07% in Table 14 to 11.74% in Table 22.

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This sharp rise shows that the aquifer model identifies more low-yield zones. It likely does so due to thin aquifer layers, high resistivity (indicating dry or compacted materials), or shallow overburden thickness.

The integrated model (Table 14) considers surface recharge and geomorphological indices. It tends to underestimate low potential zones because favourable surface features can mask poor aquifer conditions.

- *Moderate Potential Zone*

The moderate potential zone reduces from 66.90% in Table 14 to 34.93% in Table 22.

This means the integrated model's large moderate areas are reclassified. Subsurface data allow for clearer high or low-potential zones.

The integrated model provides a comprehensive hydrogeological perspective. The aquifer-based classification provides a more accurate distinction between true aquifer performance.

- *High Potential Zone*

In contrast, the high potential zone increases from 33.03% in Table 14 to 53.33% in Table 22.

This difference shows that aquifer parameters reveal more, and deeper, productive zones than those inferred from surface factors. This suggests that surface indicators sometimes underestimate potential. The aquifer characteristics confirm the presence of thick, water-saturated layers with favourable resistivity, typical of productive aquifers.

➢ *Correlation Interpretation and Discussions*

The comparison between the integrated hydrogeological model and the aquifer-based model in the Bwari region reveals a robust correlation in identifying high-potential groundwater zones (78.7% fit), consistent with findings from similar model comparison studies [91]; [92]. The aquifer-based model's higher accuracy in delineating productive areas, as shown by the shift from moderate to high-potential zones, supports previous research that emphasizes the reliability of subsurface parameter-focused assessments [93]. Meanwhile, the integrated model's value in regional recharge mapping reflects the importance of multi-criteria approaches to groundwater potential evaluation [94].

Discrepancies between the models such as the lower correlation in low-potential zones (11.7% difference) suggest that surface indicators may overestimate groundwater availability. This aligns with the observations of [95], who report that surface-based methods can lack precision in crystalline bedrock terrains. The 32% shift in the moderate class further highlights the need for refined subsurface data integration [96].

Methodological implications are significant: the study supports the assertion that parameter selection and weighting can have a strong influence on groundwater modelling outcomes [97]. The integrated model's use of thematic layers captures broad hydrogeological settings, but the aquifer-based model excels in site-specific predictions relevant for borehole siting [91].

Hydrogeologically, the expansion of high-potential zones in the aquifer-based model suggests the presence of thick, conductive, and saturated aquifer layers, echoing findings from previous studies in similar geologic settings [92]. Conversely, the identification of low-potential areas highlights the limitation of relying solely on surface indicators and the necessity of detailed subsurface analysis.

In summary, these results underscore the complementarity of both approaches. While aquifer-based models are vital for assessing groundwater storage and transmissivity, integrated models remain essential for understanding recharge and infiltration patterns. This combined methodology is widely recommended for reliable groundwater resource mapping [94]; [96].

Table 25 Summary of Comparative Assessment

Criterion	**Table 14 (Integrated)**	**Table 22 (Aquifer-Based)**	**Interpretation**
Dominant Zone	Moderate (66.90%)	Low (53.33%)	Subsurface data reveal lower productivity potential
Low Potential	0.07%	53.33%	Aquifer model identifies more poor aquifer areas
Moderate Potential	66.90%	34.93%	Reclassified into clearer high/low zones
High Potential	33.03%	11.74%	Less favourable subsurface aquifer zones detected
Overall Fitting	—	64.49%	Strong correlation between both models
Hydrogeological Significance	Reflects recharge and terrain favourability	Reflects true aquifer productivity	Complementary and mutually validating

Generally, the comparison between Tables 14 and 22 reveals a strong correlation (approximately 78.7%) between the integrated and aquifer-based groundwater potential models for the Bwari Area Council.

The aquifer model uses subsurface parameters to map more high-potential zones. This indicates a greater aquifer thickness and improved resistivity. The integrated model shows the overall hydrogeological setting.

Integrating the two models provides a comprehensive and reliable framework for groundwater potential. It balances surface recharge with aquifer productivity. This is key for exploration and management in the area.

V. CONCLUSION

This study comprehensively evaluated the groundwater potential of Bwari Area Council, FCT Abuja,

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Nigeria, through the integrated application of Vertical Electrical Sounding (VES) resistivity surveys, remote sensing, Geographic Information Systems (GIS), and the Analytical Hierarchy Process (AHP). By synergizing surface and subsurface datasets, the research provided a robust, multi-parameter framework for delineating groundwater potential zones in a challenging basement complex terrain.

The integration of geophysical, geological, hydrological, and spatial data revealed that Bwari Area Council is predominantly characterized by a dual aquifer system: a shallow weathered zone and a deeper fractured basement aquifer. The resistivity analysis, corroborated by borehole lithology, established that fractured basement rocks (400–970 Ω·m) and weathered saprolite (19–399 Ωm) are the primary groundwater reservoirs. Most productive aquifers are localized within zones of enhanced secondary porosity, controlled by weathering and fracturing, rather than by primary lithological properties alone.

Thematic mapping of key factors including slope, drainage density, lineament density, topographic wetness index, rainfall, land use/land cover, geology, and soil type demonstrated their spatial interplay in governing recharge, storage, and groundwater transmission. The AHP-based weighting and GIS overlay analysis objectively prioritized these factors, with rainfall, geology, and slope identified as the most influential controls.

Comparative analysis between the integrated (RS/GIS/thematic) model and the aquifer-parameter-based (VES) model indicated a high degree of correspondence (approximately 78.7%), confirming that both surface and subsurface indicators are essential for accurate zonation. However, the aquifer model provided finer resolution of high- and low-potential zones, highlighting the importance of incorporating direct subsurface information for groundwater development planning.

Spatially, over 85% of Bwari is classified as having moderate to high groundwater potential, with high-potential zones coinciding with areas of significant weathering, thick overburden, and dense fracture networks. Low-potential zones, though limited in extent, are associated with shallow, unweathered, or compact crystalline bedrock, underscoring the need for targeted site investigations prior to drilling.

➢ *The Results Highlight Several Important Implications:*

- Methodological Advancement: The integration of geophysical, remote sensing, GIS, and AHP techniques establishes a replicable, systematic approach for groundwater prospecting in basement complex environments.
- Hydrogeological Insight: Groundwater occurrence in Bwari is governed by the interplay of weathered mantle thickness, fracture density, overburden protection, and geomorphological factors, rather than lithology alone.
- Resource Management: The delineated potential zones offer a reliable basis for sustainable groundwater abstraction, borehole siting, and land-use planning, particularly in the context of increasing water demand.
- Model Complementarity: Employing both surface thematic and subsurface aquifer models ensures a more comprehensive and accurate representation of groundwater potential, reducing uncertainty and the likelihood of failed boreholes.

In conclusion, the integrated methodology adopted in this study not only delineates favourable groundwater zones with high spatial accuracy but also enhances the region's capacity for informed water resource management. The approach and findings serve as a model for similar hydrogeological investigations in other basement complex terrains, supporting evidence-based decision-making for sustainable development.

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