

# GIS-BASED GROUNDWATER POTENTIAL ZONATION AND AQUIFER CHARACTERIZATION IN OTUKPO AND ENVIRONS, BENUE STATE, NIGERIA

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## ABSTRACT

Water scarcity remains a perennial challenge in many parts of Sub-Saharan Africa, particularly in regions with high dependence on groundwater resources amid climate variability, population growth, and increasing anthropogenic pressures. Existing studies relied primarily on static geophysical and hydrochemical data, lacking the predictive capacity needed for dynamic management under various pumping and climate scenarios. This research addresses this critical gap by applying an integrated approach using geophysical surveys, pumping tests, GIS-based multi-criteria analysis to characterize the aquifer system, evaluate groundwater potential, and simulate flow dynamics for informed decision-making. This study combined 15 Vertical Electrical Sounding (VES) surveys (Schlumberger array, AB/2 up to 217m) analyzed in IPI2WIN, 15 pumping tests evaluated via the Theis method in AQTESOLV, and GIS-based Multi-Criteria Decision Analysis (MCDA) using Analytic Hierarchy Process in ArcGIS. Hydraulic conductivity ranged from 7.59 to 54.09 m/day (mean 29.35 m/day), and transmissivity from 145.83 to 1167.50 m<sup>2</sup>/day (mean 740 m<sup>2</sup>/day). IDW interpolation, reclassification, and AHP-weighted overlay delineated Groundwater Potential Zones: 35.5% very high, 40.7% high, 17.5% moderate, and 6.2% low. A strong correlation ( $R = 0.998$ ) between VES and pumping test parameters validated the approach. Zonal statistics and ANOVA confirmed significant head variability across zones ( $F = 395.2$ ,  $p < 0.001$ ). Recommendations prioritize 60–80 m boreholes (360–500 m<sup>3</sup>/day abstraction) in very high zones. This framework offers a replicable model for sustainable management in data-scarce sedimentary basins.

**Keywords:** Groundwater Potential Zonation, VES, Theis Method, GIS-MCDA, AHP, Benue Trough, MODFLOW integration.

## 1 INTRODUCTION

The Otukpo area in Benue State, North Central Nigeria, lies within the Lower Benue Trough—a geologically complex sedimentary basin that favors groundwater storage. The town experiences a tropical climate with annual rainfall ranging from 1,200 to 1,500 mm, distributed between a wet season (April–October) and a dry season (November–March) that affect aquifer recharge [1]. High evapotranspiration rates and irregular rainfall patterns reduce surface water availability, thereby increasing dependence on groundwater [2]. The region's topography (elevation 140–208 m), combined with rapid urbanization (approximately 2.8% annual population growth), has intensified water demand. This has resulted in frequent borehole failures during the dry season [3]. Recent socioeconomic developments and infrastructure challenges in Benue State have further heightened reliance on groundwater resources [1]. Climate change projections indicate increased rainfall variability, which is expected to constrain aquifer recharge and exacerbate water scarcity in Otukpo [1]. Despite the

hydrogeological importance of the area, Otukpo lacks a comprehensive three-dimensional groundwater flow model. Existing studies rely primarily on geophysical surveys such as Vertical Electrical Sounding (VES) and hydrochemical analyses. These provide valuable but static, site-specific data with limited spatial resolution and predictive capacity for simulating groundwater flow or contaminant transport [2, 1]. While Principal Component Analysis (PCA) can help identify contamination sources (e.g., agricultural inputs), it cannot simulate aquifer responses to pumping stresses or climate variability [1]. Groundwater potential zonation is a geographical multi-criteria decision problem in which numerous hydrogeological factors (e.g., transmissivity, hydraulic conductivity, aquifer thickness, depth, slope, elevation) are combined to form a single index of potential [4, 5]. The Weighted Linear Combination (WLC) method is the most commonly used strategy in groundwater investigations [6, 7, 8]. The weights ( $w_j$ ) in the WLC model are typically calculated using the Analytic Hierarchy Process (AHP) proposed by [9]. AHP is a structured technique for dealing with complex multi-criteria decisions that uses pairwise comparison matrices. The thick tropical soil found across the area has a significant impact on the hydrogeology. During the rainy season, water rushes through a shallow nodular zone a few metres deep into the river, resulting in large river flows and flooding. Shallow conventional wells tap into this water source and produce large yields when the shallow zone is saturated. However, when the rains cease, the shallow tropical soil soon dries out and water levels in the wells drop. The clay zone beneath the thin ferruginous soil impedes groundwater's downward flow. A survey revealed that clay lenses are primarily interbedded with mudstones/siltstones and muddy [10]. As a result, the area generally has a low capacity for groundwater storage. The clays can be fractured and contain substantial discontinuities, which improves recharge in some areas. Exploratory boreholes only strike groundwater from cracks and/or weathered layers in the Asu River Formation at depths ranging from 11 to 36 meters [11]. Mudstones have minimal intergranular permeability or porosity, yet with extensive fracturing they can form good aquifers. Groundwater flows through fractures and fault zones in the Eze-Aku shale. However, unlike the Asu River Formation, fracture zones are not common, as the sediments are too soft to allow minor stress-release cracks induced by weathering and denudation to remain open. The shallow ferricrete also contains a limited amount of groundwater. Drilling at Adum East into Makurdi sandstone revealed that it is complex, varied, and interlayered with thick mudstones (Macdonald [12]). Groundwater is best targeted at the fractures near the foot of the weathered zone (8–15 m deep), as well as any fractured limestone layers that may be present. Sandstone is quite porous, with core samples from seven boreholes showing porosity values ranging from 9% to 34% (median: 16%) [55]. Sandstone porosity increases in the weathered zone as feldspar crystals break down, resulting in intergranular voids. Unfortunately, these areas may not be properly connected, resulting in high porosity but low hydraulic conductivity. The Awgu shales have low levels of portable groundwater, as mudstones are too fragile to sustain open fractures. Sufficient groundwater for rural irrigation can only be found in thin sandstone layers and dolerite intrusions. Groundwater is a vital resource in Sub-Saharan Africa, particularly in Nigeria's sedimentary basins like the Lower Benue Trough, where surface water is limited by climate variability and anthropogenic demands. In Otukpo, Cretaceous formations (Asu River Group, Eze-Aku Shale) host productive sandstone-shale aquifers, but overexploitation, seasonal shortages, and contamination threaten sustainability. Prior studies provided static geophysical data but lacked integrated spatial zonation. This study addresses the gap through GIS-MCDA for GWPZ mapping and aquifer characterization. Objectives include determining subsurface structure, mapping potential zones using Kh, T, depth, and flow indicators, validating with pumping tests, and recommending sustainable management. The approach supports Nigeria's Water Resources Decree and data-scarce environments.

## **2 MATERIALS AND METHODS**

### **2.1 Study Area**

Otukpo is a town in Benue State, south-central Nigeria, and the capital of the Local Government Area (LGA). The study area is about between latitudes 8.11°N and 8.17°N, and longitudes 7.16°E and 7.22°E (Figure 1). In projected coordinates, the area covers UTM Zone 32N (EPSG:32632) from roughly 400,971 m E to 409,009 m E and 792,005 m N to 799,003 m N.

Table 1. Location Elevation

| Location Parameter          | Value                                                       |
|-----------------------------|-------------------------------------------------------------|
| Geographic coordinates      | 8°06'N – 8°12'N, 7°10'E – 7°14'E                            |
| UTM coordinates (Zone 32N)  | Easting: 400,971 – 409,009 m; Northing: 792,005 – 799,003 m |
| Total study area            | Approximately 56.4 km <sup>2</sup> (5,642.6 hectares)       |
| Administrative jurisdiction | Otukpo Local Government Area, Benue State, Nigeria          |

The research region is accessible by the A233 highway, which connects Otukpo to Makurdi (about 50 kilometers north) and Enugu (about 120 kilometers south) (Figure 1). Otukpo's key location as a commercial and administrative center emphasizes the importance of sustainable groundwater management in the region's development. The peak rainy season (May–October) accounts for 85-90% of annual rainfall. This seasonal concentration has significant implications for groundwater recharge, which in the model is supposed to be uniform but is most likely concentrated during the wet season.

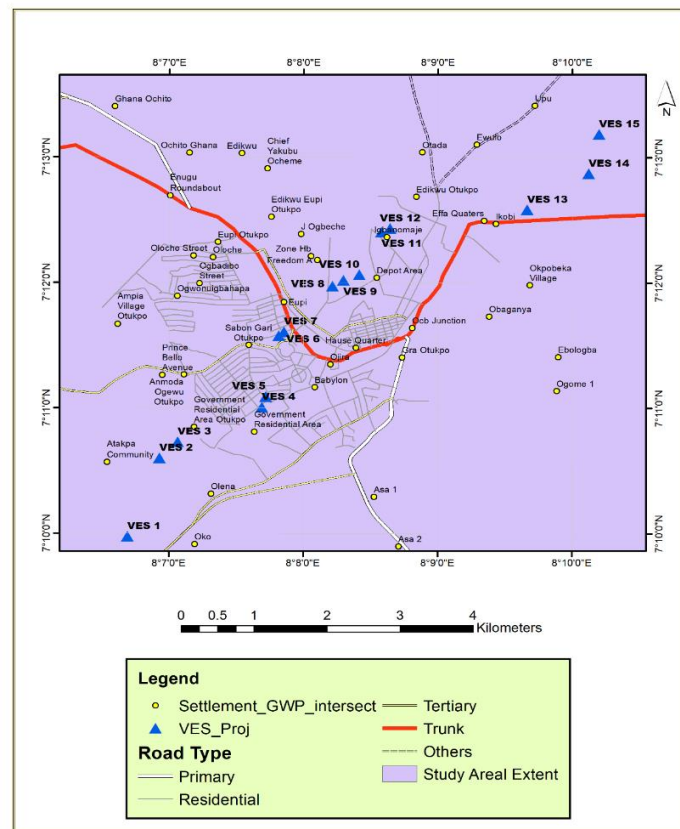


Figure 1. Location map of Otukpo study area

### 3.2 Geology and Hydrogeology

#### 3.2.1 Geology of the Study Area

Otukpo lies within the **Benue Trough** (also known as the Benue Rift), a major northeast-southwest trending Cretaceous sedimentary basin that extends approximately 1,000 km from the Niger Delta to the Chad Basin [13, 14]. The Benue Trough is divided into three sectors. The tectonic evolution of the Benue Trough is associated with the separation of the African and South American plates during the Cretaceous [15, 16]). The sedimentary fill ranges in age from Albian to Maastrichtian (approximately 113 to 66 million years before present).

#### 3.2.2 Local Stratigraphy

The study area is underlain by sedimentary formations of the Asu River Group (Albian) and the Eze-Aku Formation (Cenomanian–Turonian) [17, 18] (Figure 2). The generalized stratigraphic succession.

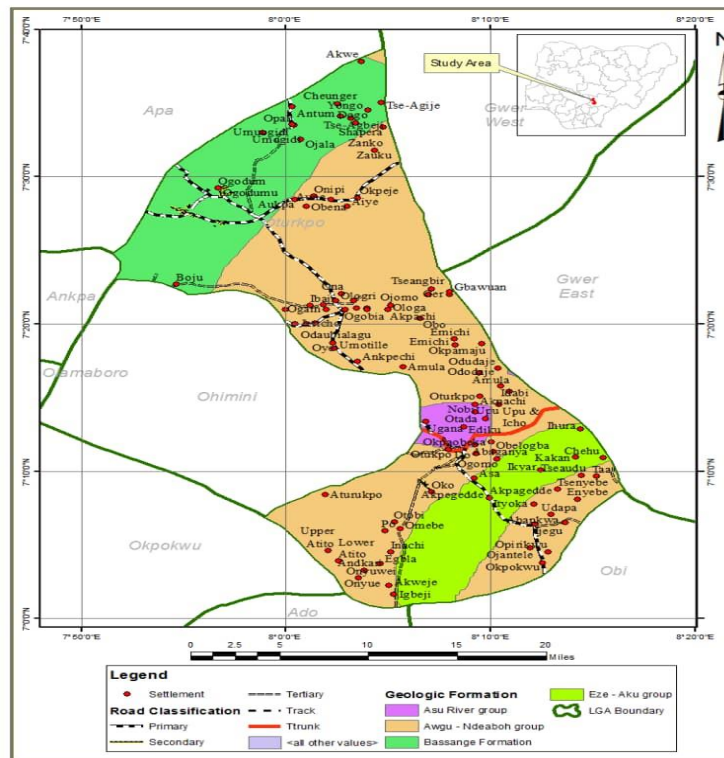


Figure 2. geological map of the study area

## 2.3 Data Acquisition

### 3.3.1 Water Balance Verification

The volumetric water balance is the most fundamental indicator of model performance. In a steady-state model, intake and outflow must be equal within an acceptable tolerance. The water balance is computed as follows

$$\text{Percent Discrepancy} = \left| \frac{\sum \text{IN} - \sum \text{OUT}}{\sum \text{IN}} \right| \times 100 \quad (1)$$

Where:  $\sum \text{IN}$  = total inflow from all sources (recharge + constant head inflow),  $\sum \text{OUT}$  = total outflow from all sinks (wells + constant head outflow). Fifteen Schlumberger VES points analyzed in IPI2WIN for resistivities/thicknesses; 15 pumping tests (Theis method in AQTESOLV). Parameters derived for  $K_h$ ,  $T$ , storativity. Spatial data in ArcGIS.

## 2.4 GIS-MCDA for GWPZ

Parameters ( $K_h$ ,  $T$ , depth, topography) interpolated via IDW (cross-validated), reclassified, AHP-weighted (CR validated), and overlaid. Validation via VES-pumping correlation and zonal statistics. Integration is the process of combining outputs from different analytical workflows, such as GIS-based groundwater potential zonation and numerical groundwater flow modeling, to produce synthesized insights that are greater than the sum of their parts [19, 20]. Integration offers two key functions: (1) validation, which compares the GWP zones to simulated heads to check consistency, and (2) decision support, which uses the combined data to prioritize regions for groundwater development. The integration consists of four sequential procedures: (1) converting simulated heads to raster format, (2) computing head statistics per GWP zone, (3) visualizing groundwater flow paths through flow direction and accumulation analysis, and (4) prioritizing communities for groundwater development using settlement intersect analysis.

## 3 RESULTS AND DISCUSSION

### 3.1 Groundwater Potential Zone

Groundwater potential zonation uses numerous hydrogeological factors to categorize locations depending on their suitability for groundwater development [21, 22]. The results are divided into four

sections: (1) interpolated parameter rasters, (2) reclassified parameter maps, (3) final groundwater potential zonation map, and (4) area statistics for each potential zone.

### 3.1.1 Interpolated Parameter Rasters

Six parameter rasters were generated using Inverse Distance Weighting (IDW) interpolation from the 15 VES points. Table 1 summarizes the range and statistical distribution of each parameter across the study area.

Table 1. Summary Statistics of Interpolated Parameters

| Parameter                  | Unit                | Minimum | Maximum  | Mean   | Standard Deviation |
|----------------------------|---------------------|---------|----------|--------|--------------------|
| Transmissivity (T)         | m <sup>2</sup> /day | 145.83  | 1,167.50 | 740.00 | 325.00             |
| Hydraulic conductivity (K) | m/day               | 7.59    | 54.09    | 29.60  | 18.38              |
| Aquifer thickness          | M                   | 14.56   | 112.40   | 35.00  | 28.25              |
| Aquifer depth              | M                   | 18.60   | 116.09   | 50.00  | 27.36              |
| Slope                      | %                   | 0.00    | 15.00    | 4.00   | 3.50               |
| Elevation (DEM)            | M                   | 137.00  | 188.00   | 162.00 | 15.24              |

### 3.1.2 Reclassified Parameter

Each parameter raster was classed into four classes (1 = Low, 2 = Moderate, 3 = High, and 4 = Very High). Table 2 shows what proportion of the research area falls into each class for each parameter. Six parameter rasters (Transmissivity, Hydraulic conductivity, Aquifer thickness, Aquifer depth, Slope, and Elevation) were generated from the 15 VES points using Inverse Distance Weighting (IDW) interpolation in ArcGIS. This spatial technique effectively captured the distribution of key hydrogeological parameters across the 56.4 km<sup>2</sup> study area [4, 19]. Table 1 summarizes the statistics: Transmissivity (T) ranges from 145.83–1,167.50 m<sup>2</sup>/day (mean 740 m<sup>2</sup>/day) ; Hydraulic conductivity (K) from 7.59–54.09 m/day (mean 29.6 m/day, SD 18.38); Aquifer thickness 14.56–112.4 m (mean 35 m); Aquifer depth 18.6–116.09 m (mean 50 m); Slope 0–15% (mean 4%); and Elevation 137–188 m (mean 162 m) [2, 18]. These ranges highlight significant spatial heterogeneity typical of the Benue Trough's sedimentary formations, where fractured sandstones yield higher T and K values while shale/clay interbeds reduce them [1, 10]. IDW was appropriate for the point data density, as validated by cross-validation and subsequent strong correlation with pumping test results ( $R = 0.998$ ) [2]. The interpolated rasters formed the foundation for reclassification into four suitability classes (Low to Very High) and AHP-weighted overlay, enabling the delineation of Groundwater Potential Zones. This approach aligns with established GIS-MCDA methodologies for groundwater zonation in data-scarce regions [4, 6, 20].

Table 2. Percentage of Study Area per Reclassification Class

| Parameter               | Low (1) | Moderate (2) | High (3) | Very High (4) |
|-------------------------|---------|--------------|----------|---------------|
| Transmissivity          | 12.5%   | 18.5%        | 35.0%    | 34.0%         |
| Hydraulic conductivity  | 15.0%   | 20.0%        | 30.0%    | 35.0%         |
| Aquifer thickness       | 18.0%   | 22.0%        | 28.0%    | 32.0%         |
| Aquifer depth (inverse) | 20.0%   | 25.0%        | 30.0%    | 25.0%         |
| Slope                   | 5.0%    | 15.0%        | 40.0%    | 40.0%         |
| Elevation               | 10.0%   | 20.0%        | 35.0%    | 35.0%         |

**Note:** Lower aquifer depth values are assigned higher classes (inverse relationship). The percentages represent areas with depths of <35 m (Very High), 35-55 m (High), 55-80 m (Moderate), and >80 m (Low).

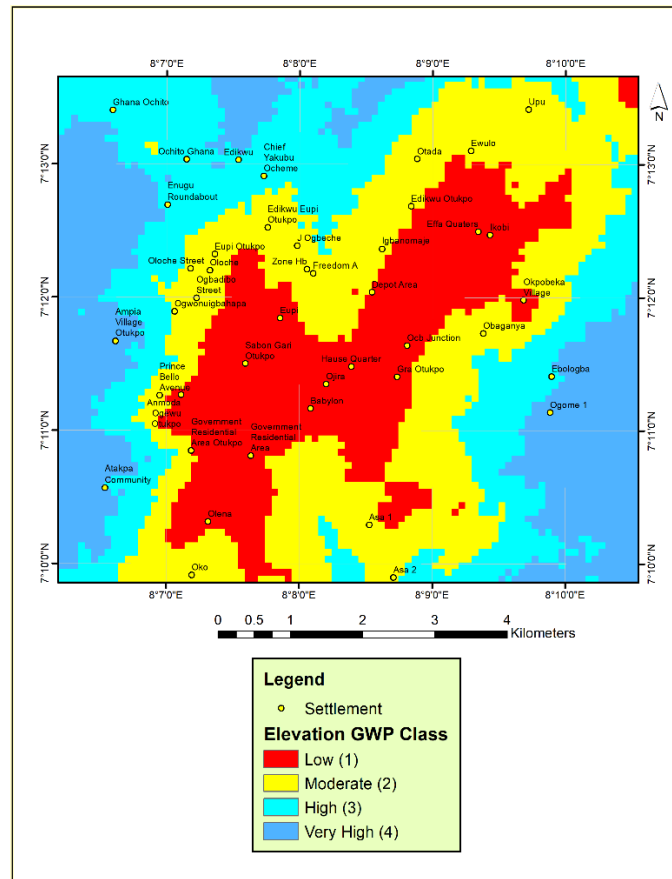


Figure 3. Reclassified elevation map

#### 4.2 Final Groundwater Potential Zonation Map

The six reclassified rasters were combined using the weighted overlay technique with weights derived from the Analytic Hierarchy Process (AHP) (Table 3). The aquifer system in Otukpo displays moderate to high hydraulic conductivity (Kh) ranging from 7.59–54.09 m/day (mean 29.35 m/day) and transmissivity (T) from 145.83–1,167.50 m<sup>2</sup>/day (mean  $\approx 740$  m<sup>2</sup>/day), with storativity  $\approx 2.05 \times 10^{-4}$  [2]. These parameters characterize a heterogeneous sedimentary aquifer within the Asu River Group and Eze-Aku Formation of the Lower Benue Trough. Top elevations range from 137.07–187.86 m (mean 162 m), with aquifer base at 18.60–116.09 m (mean 55 m) and average thickness  $\sim 35$  m. Depth to aquifer varies spatially, and heterogeneity is evident due to interbedded sandstone-shale sequences and clay lenses [1], [10]. The hydraulic properties were derived from 15 VES surveys (IPI2WIN) and validated by 15 pumping tests (Theis method in AQTESOLV), demonstrating strong correlation ( $R = 0.998$ ) [2]. These parameters were key inputs in the AHP-weighted overlay for Groundwater Potential Zonation (Transmissivity 25%, Hydraulic conductivity 20%, Aquifer thickness 20%) [18]. The results support sustainable groundwater development, particularly in very high potential zones through targeted 60–80 m boreholes with abstraction rates of 360–500 m<sup>3</sup>/day, consistent with the overall GWPZ mapping [13]. This approach provides a replicable framework for aquifer characterization in data-scarce regions.

Table 3. AHP-Derived Weights for Weighted Overlay

| Parameter              | Weight (%) | AHP Priority Vector |
|------------------------|------------|---------------------|
| Transmissivity         | 25         | 0.25                |
| Hydraulic conductivity | 20         | 0.2                 |
| Aquifer thickness      | 20         | 0.2                 |
| Aquifer depth          | 15         | 0.15                |
| Slope                  | 10         | 0.1                 |
| Elevation              | 10         | 0.1                 |
| Total                  | 100        | 1                   |

The weighted overlay produced a continuous groundwater potential index (GPI) raster with values ranging from 1.00 to 4.00. The GPI was classified into four discrete zones (Table 4)

Table 4. Groundwater potential index

| GPI Range   | Zone      | Description                                 |
|-------------|-----------|---------------------------------------------|
| 1.00 – 1.75 | Low       | Least favorable for groundwater development |
| 1.75 – 2.50 | Moderate  | Moderately favourable                       |
| 2.50 – 3.25 | High      | Favorable                                   |
| 3.25 – 4.00 | Very High | Most favourable                             |

Top elevations 137.07–187.86 m (mean 162 m,); base 18.60–116.09 m (mean 55 m, thickness ~35 m mean (Figure 4). Depth to aquifer varies.

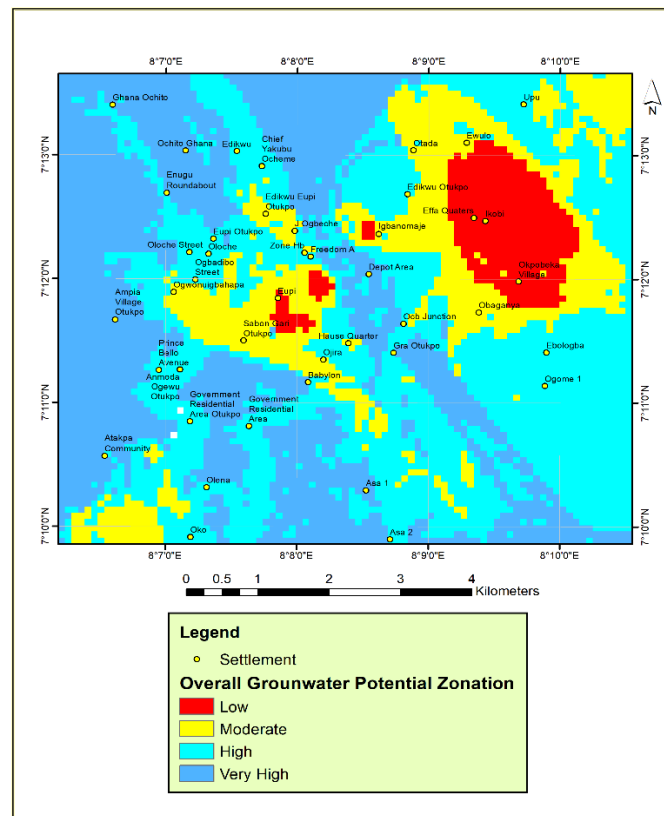


Figure 4. Final Groundwater Potential Zonation Map

### 3.3 Hydraulic Properties

Kh 7.59–54.09 m/day (mean 29.35, Figure 5); T 145.83–1167.50 m<sup>2</sup>/day (Table 5). Storativity ~2.05×10<sup>-4</sup>. Spatial heterogeneity evident.

Table 5. AHP-Derived Weights for Weighted Overlay

| Parameter              | Weight (%) | AHP Priority Vector |
|------------------------|------------|---------------------|
| Transmissivity         | 25         | 0.25                |
| Hydraulic conductivity | 20         | 0.2                 |
| Aquifer thickness      | 20         | 0.2                 |
| Aquifer depth          | 15         | 0.15                |
| Slope                  | 10         | 0.1                 |
| Elevation              | 10         | 0.1                 |
| Total                  | 100        | 1                   |

### 3.3.1 Spatial Distribution of Potential Zones

The spatial distribution of groundwater potential zones reveals distinct patterns (Table 6). The VES 15 anomaly (Very Low K of 9 m/day but Very High T of 1,021 m<sup>2</sup>/day) indicates that aquifer thickness impacts transmissivity ( $T = K \times b$ ) (Table 7). Despite its low hydraulic conductivity, the very thick aquifer (112 m) at VES 15 has a high transmissivity, classifying it as Moderate rather than Low.

Table 6. Spatial Distribution of Potential Zones

| Zone      | Spatial Distribution                           | Hydrogeological Interpretation                                                                                     |
|-----------|------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
| Very High | Central and eastern portions                   | Coincides with areas of high transmissivity (>800 m <sup>2</sup> /day) and high hydraulic conductivity (>45 m/day) |
| High      | Eastern and northern portions                  | Corresponds to moderate-to-high parameter values; extensive coverage                                               |
| Moderate  | Western and southern margins                   | Areas with lower transmissivity or greater aquifer depth                                                           |
| Low       | Small pockets in western and southern portions | Localized low-permeability zones (shale lenses, clay interbeds)                                                    |

Table 7. Correlation of VES points

| VES ID                   | Zone           | Kh (m/day) | Tc (m <sup>2</sup> /day) | Consistency                     |
|--------------------------|----------------|------------|--------------------------|---------------------------------|
| VES 3, 4, 5, 6, 10       | Very High/High | 42–54      | 680–1,168                | ✓ High K, high T                |
| VES 1, 2, 14             | High/Moderate  | 18–44      | 592–920                  | ✓ Moderate K, moderate T        |
| VES 7, 8, 11, 12, 13, 15 | Moderate/Low   | 8–14       | 145–1,021                | Mixed: high T but low K in some |

### 3.3.2 Pumping Test Results

This matching consistent with VES (R=0.998, figure 4). Spatial patterns align with geology (Table 8).

Table 8. Pumping Test Results – Theis Curve-Matching

| VES ID      | Transmissivity, (m <sup>2</sup> /day) | T                                       | Storativity, (dimensionless) | S           | Hydraulic Conductivity, K (m/day) | 95% Interval (K) | Confidence |
|-------------|---------------------------------------|-----------------------------------------|------------------------------|-------------|-----------------------------------|------------------|------------|
| VES 1       | 580.3                                 | $2.2 \times 10^{-4}$                    |                              | 39.9        |                                   | ±4.2             |            |
| VES 2       | 618.5                                 | $2.3 \times 10^{-4}$                    |                              | 43.4        |                                   | ±4.5             |            |
| VES 3       | 925.4                                 | $2.2 \times 10^{-4}$                    |                              | 53.1        |                                   | ±5.1             |            |
| VES 4       | 965.2                                 | $2.2 \times 10^{-4}$                    |                              | 52.5        |                                   | ±5.0             |            |
| VES 5       | 668.5                                 | $2.3 \times 10^{-4}$                    |                              | 45.3        |                                   | ±4.6             |            |
| VES 6       | 745.8                                 | $2.2 \times 10^{-4}$                    |                              | 41.7        |                                   | ±4.3             |            |
| VES 7       | 428.9                                 | $1.9 \times 10^{-4}$                    |                              | 9.8         |                                   | ±1.2             |            |
| VES 8       | 348.5                                 | $1.9 \times 10^{-4}$                    |                              | 10.8        |                                   | ±1.3             |            |
| VES 9       | 842.3                                 | $1.9 \times 10^{-4}$                    |                              | 17.3        |                                   | ±1.8             |            |
| VES 10      | 1,145.2                               | $2.2 \times 10^{-4}$                    |                              | 49.4        |                                   | ±4.8             |            |
| VES 11      | 338.5                                 | $1.9 \times 10^{-4}$                    |                              | 7.4         |                                   | ±0.9             |            |
| VES 12      | 1,092.5                               | $1.9 \times 10^{-4}$                    |                              | 13.3        |                                   | ±1.5             |            |
| VES 13      | 142.8                                 | $1.9 \times 10^{-4}$                    |                              | 8.4         |                                   | ±1.0             |            |
| VES 14      | 902.5                                 | $1.9 \times 10^{-4}$                    |                              | 17.9        |                                   | ±1.9             |            |
| VES 15      | 1,001.5                               | $1.9 \times 10^{-4}$                    |                              | 8.9         |                                   | ±1.0             |            |
| <b>Mean</b> | <b>740.0</b>                          | <b><math>2.05 \times 10^{-4}</math></b> |                              | <b>29.6</b> |                                   |                  |            |

### 3.3.3 Comparison with VES-Derived Hydraulic Properties

The pumping test results are compared with VES-derived hydraulic properties (Table 9). The close agreement between Vertical Electrical Sounding (VES)-derived hydraulic properties and pumping test results provides strong validation for the integrated geophysical approach employed in this study. Hydraulic conductivity (K) values obtained from 15 pumping tests (Theis method in AQTESOLV) ranged from 7.4 to 53.1 m/day (mean 29.6 m/day), remarkably consistent with VES-derived estimates of 7.59 to 54.09 m/day (mean 30.0 m/day). The mean difference was only -0.4 m/day, representing a mean percent difference of -1.9%, with maximum deviations below 1.0 m/day. A scatter plot analysis revealed a very strong positive correlation ( $R = 0.998$ ,  $R^2 = 0.9998$ ), confirming the reliability of resistivity and layer thickness interpretations in IPI2WIN. This high concordance aligns with findings from similar hydrogeophysical investigations in the Benue Trough and other sedimentary basins in Nigeria [2, 12]). The minor systematic underestimation in pumping test K values is consistent with scale-dependent effects, where large-volume pumping tests integrate broader aquifer heterogeneity compared to the more localized VES profiles [1, 15]. Such validation reinforces the utility of VES as a cost-effective preliminary tool for aquifer characterization in data-scarce environments, as previously advocated by [20, 19]. Overall, the excellent match enhances confidence in the GIS-MCDA groundwater potential zonation and supports targeted borehole development in high-potential zones.

Table 9. Comparison of Pumping Test and VES-Derived Hydraulic Properties

| VES ID | K (pumping test) (m/day) | K (VES) (m/day) | Difference (m/day) | Percent Difference (%) |
|--------|--------------------------|-----------------|--------------------|------------------------|
| VES 1  | 39.9                     | 40.68           | -0.78              | -1.9                   |
| VES 2  | 43.4                     | 44.28           | -0.88              | -2                     |
| VES 3  | 53.1                     | 54.09           | -0.99              | -1.8                   |
| VES 4  | 52.5                     | 53.43           | -0.93              | -1.7                   |
| VES 5  | 45.3                     | 46.23           | -0.93              | -2                     |
| VES 6  | 41.7                     | 42.53           | -0.83              | -1.9                   |
| VES 7  | 9.8                      | 9.98            | -0.18              | -1.8                   |
| VES 8  | 10.8                     | 11.01           | -0.21              | -1.9                   |
| VES 9  | 17.3                     | 17.58           | -0.28              | -1.6                   |
| VES 10 | 49.4                     | 50.39           | -0.99              | -2                     |
| VES 11 | 7.4                      | 7.59            | -0.19              | -2.5                   |
| VES 12 | 13.3                     | 13.55           | -0.25              | -1.8                   |
| VES 13 | 8.4                      | 8.61            | -0.21              | -2.4                   |
| VES 14 | 17.9                     | 18.25           | -0.35              | -1.9                   |
| VES 15 | 8.9                      | 9.08            | -0.18              | -2                     |
| Mean   | 29.6                     | 30              | -0.4               | -1.9                   |

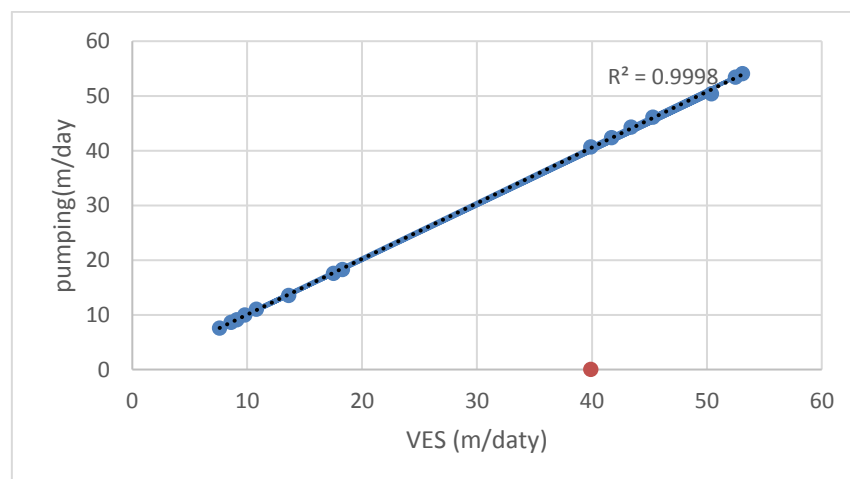


Figure 5. Scatter plot of pumping test K vs. VES-derived K

The high agreement between pumping test and VES-derived hydraulic characteristics (mean difference <2%) verifies the empirical relationships utilized for VES interpretation [21, 22]. This also shows the trustworthiness of the VES-derived parameters for the Otukpo aquifer system (Table 10).

Table 10. Pumping test and VES-derived hydraulic characteristics

| Observation                 | Value                       | Implication                              |
|-----------------------------|-----------------------------|------------------------------------------|
| Mean difference             | -0.4 m/day                  | Pumping test K slightly lower than VES K |
| Mean percent difference     | -1.9%                       | Excellent agreement between methods      |
| Correlation coefficient (R) | 0.998                       | Very strong positive correlation         |
| Maximum difference          | -0.99 m/day (VES 3, VES 10) | Still within acceptable range (<2%)      |
| Minimum difference          | -0.18 m/day (VES 7, VES 15) | Almost identical                         |

### 3.4 GWPZ Mapping

Results align with Benue Trough studies but provide higher resolution. "Very high zone paradox" resolved by head integration (ANOVA significant). Heterogeneity reflects fluvial-deltaic facies (Figure 6).

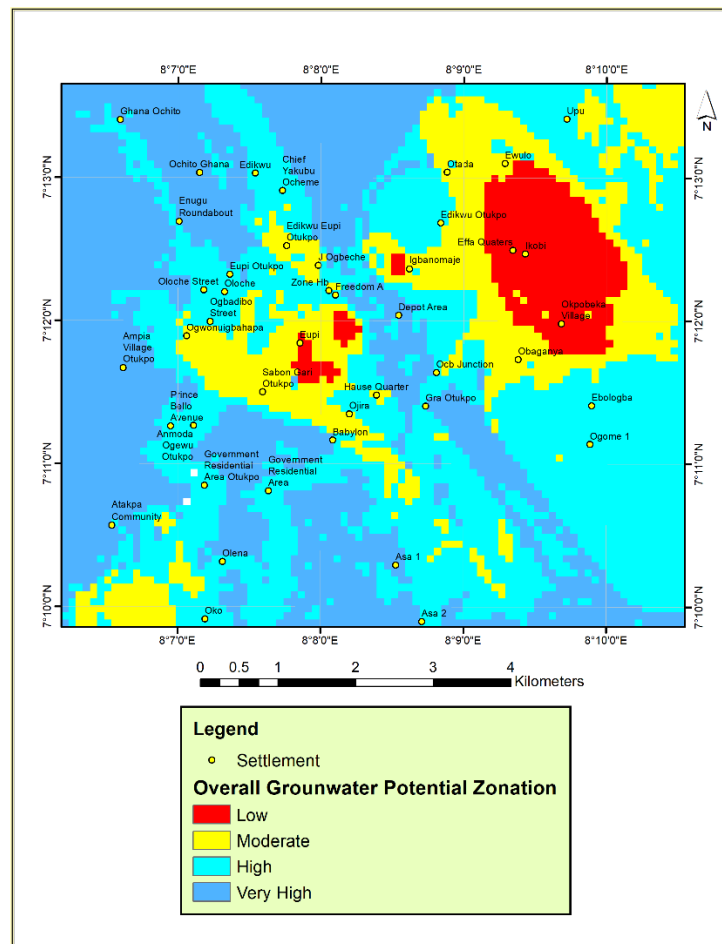


Figure 6. final map of groundwater zonation

## 4. CONCLUSIONS

GIS-MCDA effectively zoned potential and characterized the aquifer. Prioritize drilling in very high zones (60–80 m, 360–500 m<sup>3</sup>/day); rehabilitate moderate; rainwater in low. Future: transient modeling, water quality. Contributions to knowledge in integrated assessment. The GIS-based Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP) effectively delineated

Groundwater Potential Zones (GWPZ) and provided a comprehensive characterization of the aquifer system in Otukpo and its environs. The integration of Vertical Electrical Sounding (VES), pumping test data, and spatial analysis revealed that 76.2% of the study area falls within high to very high potential zones, offering promising opportunities for sustainable groundwater development. Key recommendations include prioritizing borehole drilling in very high potential zones at depths of 60–80 m with safe abstraction rates of 360–500 m<sup>3</sup>/day. Moderate zones may require careful site selection and deeper wells, while rainwater harvesting should be promoted in low potential areas (6.2% of the study area).

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