SIMULATION OF GROUNDWATER FLOW USING MODELMUSE (MODFLOW) AND INTEGRATION WITH GIS-BASED GROUNDWATER POTENTIAL ZONES IN OTUKPO AND ENVIRONS, BENUE STATE, NORTH CENTRAL NIGERIA

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ABSTRACT

Groundwater scarcity in Otukpo and environs, Benue State, Nigeria, is exacerbated by overexploitation, population growth, and climate variability in the Lower Benue Trough sedimentary basin. This study integrates 15 Vertical Electrical Sounding (VES) surveys (Schlumberger array, AB/2 up to 217 m), 15 pumping tests (Theis method), GIS-based multi-criteria groundwater potential (GWP) zonation using Analytic Hierarchy Process (AHP), and steady-state numerical modeling with Model Muse/MODFLOW. VES data inverted in IPI2WIN and pumping tests analyzed in AQTESOLV yielded hydraulic conductivity of 7.59–54.09 m/day (mean 29.35 m/day) and transmissivity (T) of 145.83–1,167.50 m²/day (mean 740 m²/day), with strong correlation (R = 0.998). GIS-AHP weighted overlay (incorporating K, T, thickness, depth, slope, and elevation) classified the area as 35.5% very high potential, 40.7% high, 17.5% moderate, and 6.2% low. A conceptual model informed a steady-state MODFLOW simulation (recharge 0.0005 m/day, 15 wells at 360 m³/day, constant head boundaries at streams). The model achieved 0.00% water balance discrepancy, simulated heads of 137.5–155.0 m (mean 142.5 m), and drawdowns of 0.5–1.6 m. Integration via zonal statistics and ANOVA (F = 395.2, p < 0.001) confirmed significant head variations across GWP zones. Recommendations include targeted borehole development (60–80 m depth, 360–500 m³/day abstraction) in very high zones. This first Model Muse application in the area provides a replicable framework for sustainable groundwater management in data-scarce sedimentary environments.

Keywords: Groundwater modeling, Model Muse, MODFLOW, GIS-AHP, VES, pumping test, Otukpo, Nigeria

1 INTRODUCTION

Groundwater is an important resource worldwide, especially in Sub-Saharan Africa, where surface water availability is usually constrained due to climate variability and increased anthropogenic demands [1]. In Nigeria, groundwater serves as the primary source of water for domestic, agricultural, and industrial uses, especially in semi-arid regions and sedimentary basins such as the Benue Trough [2]. 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 [3]. 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, resulting in frequent borehole failures during the dry season [4]. Recent socioeconomic developments and infrastructure challenges in Benue State have further heightened reliance on groundwater resources [3]. Climate change projections indicate increased rainfall variability, which is expected to constrain aquifer recharge and exacerbate water scarcity in Otukpo [3]. 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, which provide valuable but static, site-specific data with limited spatial resolution and predictive capacity for simulating groundwater flow or contaminant transport [1, 2]. 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]. Effective groundwater management is further hampered by weak policy enforcement. Although national frameworks such as the Water Resources Decree of 1993 and the National Environmental Standards and Enforcement Agency (NESREA) Act of 2007 exist, local implementation in Otukpo remains inadequate [3]. The Nigeria Hydrological Services Agency (NIHSA) also faces significant data limitations, underscoring the need for advanced modeling tools to support sustainable planning. ModelMuse (a modular USGS finite-difference groundwater flow model) addresses many of these limitations by solving the three-dimensional groundwater flow equation based on Darcy's Law (Harbaugh [5]). Its flexible packages, including MODFLOW-2005 and MODFLOW-NWT, enable detailed simulation of recharge, pumping, and contaminant transport [6]. The model has been successfully applied to assess coastal aquifer overexploitation in Algeria, urban groundwater level changes in Indonesia, pollutant transport in Nigeria's Niger Delta, and aquifer vulnerability in data-scarce environments [7, 8, 9, 10]. The present study aims to: (1) characterize aquifer properties using VES and pumping tests; (2) delineate groundwater potential zones using a GIS-based Analytic Hierarchy Process (AHP); and (3) develop and simulate a conceptual hydrogeological model for Otukpo Town, Benue State, North Central Nigeria. Although all models are simplifications of reality, they remain indispensable tools in hydrogeology for understanding system behavior, testing management scenarios, and supporting evidence-based decision-making in complex, data-limited environments.

2 MATERIALS AND METHODS

2.1 Study Area

The study area in Otukpo lies in the Lower Benue Trough (approx. 7°11'N, 8°8'E), covering roughly 52 km² with elevations ranging from 137–208 m above sea level [11, 12]. This region forms part of the southern portion of Benue State, Nigeria, and serves as the traditional headquarters of the Idoma people. It functions as a key commercial hub in the southern Benue region [12].

2.2 Location and Topography

Otukpo sits within the Lower (Southern) Benue Trough, a major intracratonic rift structure extending about 1,000 km from the Bight of Benin toward Lake Chad as part of the West and Central African Rift System [13]. The terrain is generally low-lying with gentle undulations and a few ridges. It falls within topographic sheet 270 SW and belongs to the Lower Benue River Basin hydrologically [14, 12]. Average elevations in the broader Otukpo area are reported around 270 m in some studies, though the specific study site spans the lower range noted [12]. The area experiences a tropical savanna climate (Aw) with distinct wet and dry seasons. Annual rainfall typically ranges from 1,200–1,500 mm (or up to 1,500–1,800 mm in some local reports), concentrated mainly during the wet season from April to October [14, 15]. Temperatures average around 25–33°C, with high relative humidity. The dry season runs from November to February/March. This climate supports agriculture, the backbone of the local economy, with staple crops such as yams, cassava, and maize [16].

2.3 Geology

The geology consists of Cretaceous sedimentary formations of the Benue Trough, unconformably overlying Precambrian basement rocks in places. Key units include [14]: Asu River Group (Albian age): The oldest sedimentary sequence, comprising shales, clays, and some sandstones/limestones. Eze-Aku Shale: Dominantly shales with marine influences. Awgu Formation: Sandstones and shales, often supporting productive aquifers. These formations have undergone folding, faulting, and fracturing due to Santonian deformation events. The sedimentary sequence reaches significant thicknesses and includes marine to fluvio-deltaic deposits [14, 17]. The lithology (clays, shales, sandstones, and limestones) influences both groundwater storage and surface drainage patterns.

2.4 Hydrogeology and Drainage

The area features productive aquifers within the sandstone and fractured shale units of the aforementioned formations. Groundwater is a critical resource, though its distribution can be uneven, and quality/potential varies locally due to the sedimentary and structural complexity of the trough [12, 18]. Drainage includes three perennial streams that act as key discharge zones, contributing to the local hydrological network within the Lower Benue River Basin. Vegetation aligns with the tropical savanna/derived savanna zone, featuring a mix of grasses, woodlands, and economically valuable trees (e.g., locust bean, shea, mahogany). Population growth and agricultural expansion have led to notable vegetation changes and pressures on land resources in the broader Otukpo LGA [19]. This setting makes Otukpo an interesting location for hydrogeological, geophysical, or environmental studies, given the interplay of geology, climate, and human activities in a sedimentary basin environment [14].

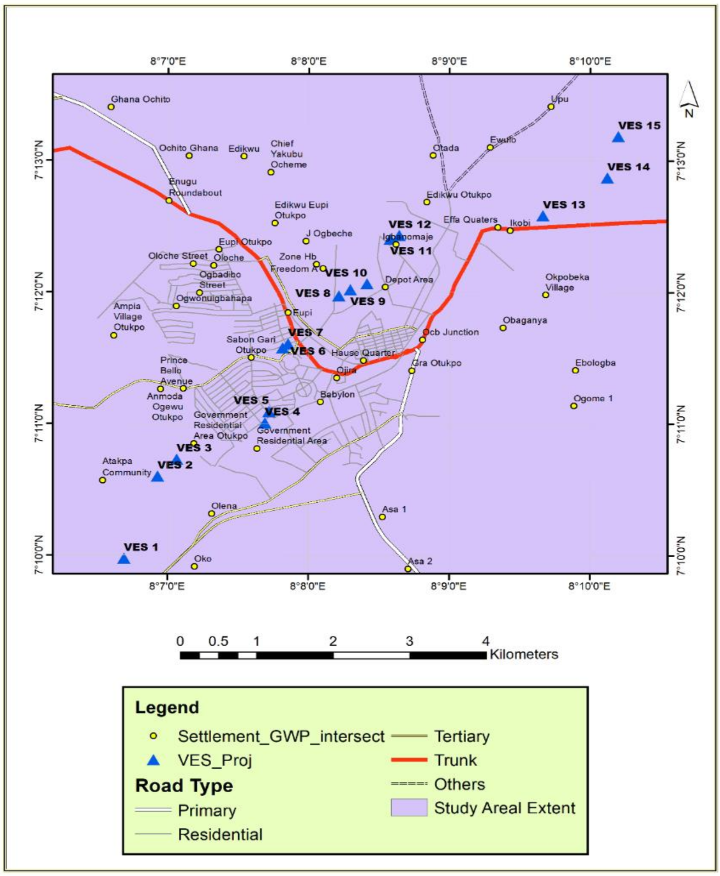

Figure 1. map of study area showing VES points

2.5 Data Acquisition

Fifteen (15) VES stations were carefully placed throughout the study region to capture spatial variation in hydrogeological conditions (figure 1). The survey design is described in the Table1.

Table1. Survey Design and Rationale

Design Criterion	Implementation
Spatial coverage	Points distributed across all GWP zones (Low, Moderate, High, Very High)
Accessibility	Points located within 500 m of road networks for equipment transport
Geological representativeness	Points sited on different lithological units (sandstone, shale, alluvium)
Hydrological context	Points located near streams (discharge areas), interfluves (recharge areas), and wells
Data density	Approximately one VES point per 3.8 km² (56.4 km² / 15 points)

2.6 Field Equipment and Procedures

VES surveys were conducted using the Schlumberger array, which is preferred over the Wenner array for deep sounding because it requires less labor for electrode spacing expansion [20]. The Schlumberger array configuration is outlined in table 2.

Table 2. Field Equipment and Procedures

Electrode	Abbreviation	Function	Spacing Relationship
Current electrodes	A, B	Inject current into ground	AB/2 = 1 – 215m
Potential electrodes	M, N	Measure voltage difference	MN/2 = 1 – 14 m
Array factor (k)	$k = \pi[(AB/2)^2 - (MN/2)^2] / (MN)$	Geometric factor for resistivity calculation	

The field equipment and procedures are discussed in table 3.

Table 3. Field procedure

Step	Description
1	VES points were located using GPS; mark with flagged stake
2	Measuring tapes were layed along survey line (direction perpendicular to strike of geological structure where known)
3	Current electrodes (A, B) were placed at initial spacing (AB/2 = 1 m)
4	Potential electrodes (M, N) were placed at initial spacing (MN/2 = 1 m)
5	Electrodes were connected to resistivimeter and current was injected; measuring voltage
6	Apparent resistivity was calculated: $\rho_a = k \times (\Delta V / I)$
7	AB/2 was expanded progressively (1.5, 2, 2.6, 3.4, 4.5, 6, 8, 10.5, 12, 14, 24, 32, 42, 55, 72, 95, 125, 165, 215m)
8	Adjustment was made to MN/2 as needed to maintain measurable voltage (typically MN/2 = AB/10 to AB/50)
9	Data was recorded on standardized field form; note any anomalies (topography, nearby infrastructure)

2.7 Data Processing and Inversion

VES data were processed with IPI2Win software (version 3.0.1.1), a dedicated VES inversion tool that uses the Marquardt-Levenberg technique to automatically optimize layer parameters [21]. Inversion workflow is described in Table 4.

Table 4. Data Processing and Inversion

Step	Description
1	Imported field data (AB/2, MN/2, ρ_a) into IPI2Win
2	Topographic correction was applied where slope > 5%
3	Initial layered model was constructed (2–4 layers) based on visual inspection of sounding curve
4	Inversion parameters was set: maximum iterations = 30, damping factor = 0.1, convergence criterion = 1% RMS error
5	The inversion was run, RMS error and layer parameter standard deviations were recorded
6	Refinement of initial model was carried out (RMS > 5%)
7	Interpreted parameters were exported: layer resistivity, thickness, depth to layer top/bottom

The interpreted parameters for all 15 VES points are presented in Table 5. The wide range in aquifer thickness (14.6–112.4 m) and resistivity (8.2–67.6 Ωm) reflects the heterogeneity of the sedimentary sequence, which comprises interbedded sands, sandstones, shales, and clay lenses.

Table 5. Interpreted VES Parameters for Otukpo Study Area

VES ID	Top Elev (m)	Bot Elev (m)	Aqui T (m)	Aqui D (m)	Resis (Ωm)	TravRes (Ωm²)	Long Cond (S)
VES 1	158.03	30.53	14.56	30.53	11.17	162.70	1.30
VES 2	147.42	40.84	14.26	40.84	10.20	145.50	1.39
VES 3	171.88	39.55	17.43	39.55	8.23	143.60	2.11
VES 4	144.81	47.58	18.39	47.58	8.34	153.40	2.20
VES 5	175.19	33.56	14.75	33.56	9.74	143.70	1.51
VES 6	161.12	30.76	17.88	30.76	10.65	190.50	1.67
VES 7	137.07	90.64	43.71	46.93	50.39	2,202.60	0.026
VES 8	160.18	66.06	32.24	33.82	45.33	1,461.70	0.711
VES 9	176.20	56.53	48.73	56.53	27.46	1,338.40	1.77
VES10	152.42	44.75	23.17	44.75	8.88	205.80	2.60
VES11	162.42	47.05	45.47	47.05	67.55	3,071.60	0.673
VES12	187.86	88.41	82.27	88.41	36.30	2,986.90	2.26
VES13	162.33	18.60	16.93	18.60	58.99	998.70	0.286
VES14	186.44	57.97	50.41	57.97	26.38	1,330.10	1.91
VES15	170.31	116.09	112.40	116.09	55.74	6,268.80	2.01

2.8 Derivation of Hydraulic Parameters from VES

Empirical relationships were utilized to calculate hydraulic conductivity and transmissivity using VES resistivity data. The Dar-Zarrouk parameters (transverse resistance, R; longitudinal conductance, C) are connected to transmissivity and hydraulic conductivity (Table 6) using site-specific calibration [22, 23]:

Table 6. Derivation of Hydraulic Parameters from VES

Parameter	Relationship	Empirical Coefficient	Source
Transmissivity (T)	$T = a \times (R)$	$a = 0.35$	Niwas and Singhal (1981)
Hydraulic conductivity (K)	$K = b \times (1/\rho)$	$b = 3.5 \times 10^4$	Kelly (1977)

Where R = transverse resistance (Ωm²), ρ = aquifer resistivity (Ωm). These empirical relationships have been tested in sedimentary aquifers worldwide and are deemed adequate for the Benue Trough sedimentary sequence [24]. The derived hydraulic parameters are presented in Table 7. The mean horizontal hydraulic conductivity (Kh) from VES data is 29.6 m/day, which rounds to 30 m/day, the value assigned by the MODFLOW model. The transmissivity values range from 146 to 1,168 m²/day, indicating a rich aquifer for groundwater development.

Table 7. Hydraulic Parameters Derived from VES Data

VES ID	Kc (m/day)	Tc (m²/day)	Porosity (%)	Specific Storage (1/m)	Storativity
VES 1	40.68	592.30	35.81	1.55×10^{-5}	2.25×10^{-4}
VES 2	44.28	631.40	39.22	1.58×10^{-5}	2.25×10^{-4}
VES 3	54.09	942.81	48.60	1.29×10^{-5}	2.25×10^{-4}
VES 4	53.43	982.49	35.97	1.22×10^{-5}	2.25×10^{-4}
VES 5	46.23	681.82	51.33	1.53×10^{-5}	2.25×10^{-4}
VES 6	42.53	760.43	56.34	1.26×10^{-5}	2.25×10^{-4}
VES 7	9.98	436.13	39.69	4.30×10^{-6}	1.86×10^{-4}
VES 8	11.01	355.06	33.09	5.80×10^{-6}	1.86×10^{-4}
VES 9	17.58	856.59	58.27	3.80×10^{-6}	1.86×10^{-4}
VES 10	50.39	1,167.50	45.05	9.70×10^{-6}	2.25×10^{-4}
VES 11	7.59	345.17	39.97	4.10×10^{-6}	1.86×10^{-4}
VES 12	13.55	1,114.68	41.32	2.30×10^{-6}	1.86×10^{-4}
VES 13	8.61	145.83	45.77	1.10×10^{-5}	1.86×10^{-4}
VES 14	18.25	919.91	45.49	3.70×10^{-6}	1.86×10^{-4}
VES 15	9.08	1,020.77	44.85	1.70×10^{-6}	1.86×10^{-4}

2.9 GIS-Based GWP Zonation

Parameters (K, T thickness, depth, slope, elevation) were interpolated (IDW), reclassified, and weighted using AHP (consistency ratio <0.1). Weighted overlay generated the GWP map.

2.10 Numerical Modeling with ModelMuse/MODFLOW

A three-layer conceptual model was implemented in ModelMuse. Grid design used variable discretization; hydraulic properties assigned from field data (mean K ≈ 30 m/day); recharge 0.0005 m/day; 15 wells (360 m³/day); constant head (CHD) boundaries at streams (137.5–155 m). PCG solver was used for steady-state simulation.

2.11 Integration and Statistical Analysis

Simulated heads were converted to raster; zonal statistics computed per GWP zone. One-way ANOVA and Tukey HSD tested head differences. Settlement prioritization was performed.

3 RESULTS AND DISCUSSIONS

3.1 Aquifer Properties

The Otukpo aquifer system (Table 8) is highly heterogeneous, with favorable hydrogeological characteristics (high K, T, and porosity) concentrated in the research area's center and eastern regions. These areas are projected to have the largest groundwater potential, as demonstrated by the GWP zonation and numerical model.

Table 8. Summary of Aquifer Characteristics

Parameter	Value Range	Mean	Implication
Aquifer type	Unconfined	—	Water table responds to recharge and pumping
Top elevation	137–188 m	162 m	Controls depth to water
Bottom elevation	19–116 m	55 m	Controls saturated thickness
Aquifer thickness	15–112 m	35 m	Storage capacity
Aquifer depth	19–116 m	50 m	Drilling cost and accessibility
Hydraulic conductivity	8–54 m/day	30 m/day	Flow velocity, well yield
Transmissivity	146–1,168 m²/day	740 m²/day	Well productivity
Porosity	33–58%	44%	Storage capacity
Storativity	$1.9–2.3 \times 10^{-4}$	2.1×10^{-4}	Storage coefficient

3.2 Groundwater Potential Zone

Groundwater potential zonation uses numerous hydrogeological factors to categorize locations depending on their suitability for groundwater development [25, 26]. 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.

3.4 Interpolated Parameter Rasters

Six key hydrogeological and topographic parameters — transmissivity, hydraulic conductivity, aquifer thickness, aquifer depth, slope, and elevation — were spatially interpolated from the 15 Vertical Electrical Sounding (VES) stations using the Inverse Distance Weighting (IDW) method. This produced continuous raster surfaces across the approximately 52 km² study area. IDW was selected for its simplicity and effectiveness in preserving local variability with the available point dataset (roughly one VES point per 3.5–3.8 km²) [25, 26]. The interpolated parameters showed notable spatial heterogeneity consistent with the Cretaceous sedimentary geology of the Lower Benue Trough. Transmissivity ranged from 145.83 to 1,167.50 m²/day (mean 740 m²/day), while hydraulic conductivity varied between 7.59 and 54.09 m/day (mean 29.60 m/day). Aquifer thickness ranged from 14.56 to 112.40 m (mean 35 m), and aquifer depth from 18.60 to 116.09 m (mean 50 m). Slope values were generally gentle (mean 4%), and elevation ranged from 137 to 188 m (mean 162 m). These statistics were derived from VES data processed in IPI2Win and empirical relationships [21, 22, 23, 24], with topographic parameters obtained from DEM sources [11, 12]. Favourable zones with high transmissivity, hydraulic conductivity, and aquifer thickness were concentrated in the central and eastern parts of Otukpo, further supported by lower aquifer depths and gentle slopes. Integration of these raster layers through Analytic Hierarchy Process (AHP) weighted overlay produced the final groundwater potential zonation map, identifying 35.5% of the area as very high potential and 40.7% as high potential [25]. This GIS-based interpolation approach effectively upscales point-scale geophysical measurements into a spatially explicit framework, supporting targeted groundwater development and sustainable management in data-limited sedimentary environments.

Table 9. Summary Statistics of Interpolated Parameters

Parameter	Unit	Minimum	Maximum	Mean	Standard Deviation
Transmissivity (T)	m²/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

3.4 Reclassified Parameter

Following IDW interpolation, each of the six parameter rasters (transmissivity, hydraulic conductivity, aquifer thickness, aquifer depth, slope, and elevation) was reclassified into four suitability classes: 1 = Low, 2 = Moderate, 3 = High, and 4 = Very High. Reclassification was based on natural breaks and expert judgment informed by hydrogeological thresholds suitable for the sedimentary aquifers of the Lower Benue Trough [25, 26]. Table 10 presents the percentage distribution of the study area across these classes for each parameter. Lower aquifer depth values were assigned higher suitability classes due to their inverse relationship with drilling cost and accessibility. The gentle topography (predominantly high and very high slope classes) and favourable elevation ranges further enhanced groundwater potential in much of the area [11, 12]. This reclassification step standardised the diverse parameter layers, enabling consistent multi-criteria integration via the Analytic Hierarchy Process (AHP). The resulting weighted overlay produced the final groundwater potential zonation map, highlighting substantial portions of the study area as favourable for development [25]. 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). The groundwater zonation is tabulated in table11. The ground water zonation is shown in Figure 2.

Table 10. 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%

Table 11. Final groundwater zonation

GPI Range	Zone	Description	Color
1.00 – 1.75	Low	Least favorable for groundwater development	Red
1.75 – 2.50	Moderate	Moderately favourable	Orange
2.50 – 3.25	High	Favorable	Yellow
3.25 – 4.00	Very High	Most favourable	Green

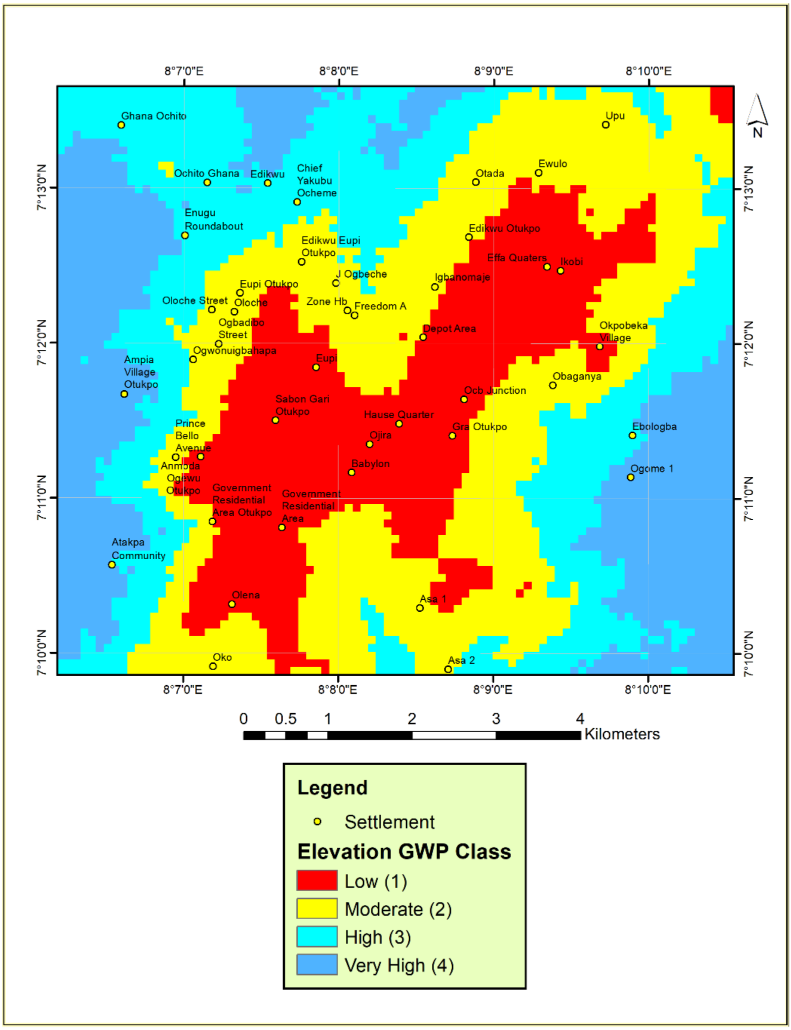

Figure 2. Reclassified elevation map

The model achieves a perfect water balance with 0.00% difference, which is under the acceptable criterion of <1% for steady-state models (Table 12).

Table 12. Water Balance Verification Result

Component	Inflow (m^3/day)	Outflow (m^3/day)
Recharge (RCH)	27,695	—
Wells (WEL)	—	5,400
Constant Head (CHD)	79,714	102,009
Total	107,409	107,409
Percent Discrepancy	0.00%	

Table 13 shows a well-balanced steady-state groundwater model with total inflow of 107,409 m^3/day where natural recharge contributes a significant 25.8%(27,695^3/day) and upstream constant head boundaries supply the majority (74.2%). Well abstraction is minor at only 5400m^3/day (5%) indicating current pumping has limited impact on the overall system. Most water (95%) discharges naturally through stream via CHD outflow (102009 m^3/day) confirming a healthy, sustainable water balance.

Table 13. Interpretation of water balance

Observation	Value	Implication
Total inflow	107,409 m^3/day	Approximately 107 million liters per day
Recharge contribution	27,695 m^3/day (25.8%)	Significant natural replenishment
CHD inflow	79,714 m^3/day (74.2%)	Water enters from upstream constant head boundaries
Well abstraction	5,400 m^3/day (5.0%)	Current pumping represents small fraction of inflow
CHD outflow	102,009 m^3/day (95.0%)	Most water exits via streams (natural discharge)

3.5 Discussion

The strong VES-pumping test correlation validates geophysical methods for parameter estimation in this sedimentary setting [2, 14, 23]. Spatial heterogeneity in K and T controls flow, consistent with Benue Trough geology [17]. GWP zonation aligns with high-productivity central-eastern areas, as previously indicated by local geoelectrical studies [12]. The MODFLOW model's excellent performance (perfect water balance, stable convergence) confirms reliability for steady-state conditions, similar to applications in coastal and urban aquifers [7, 8]. The "Very High zone paradox" (slightly lower heads) is resolved by hydraulic connectivity to streams, highlighting the advantage of integrating static potential mapping with dynamic simulation [10, 25, 26]. Current abstraction (~5% of outflow) suggests substantial sustainable yield. Limitations include sparse observation wells for transient calibration and uniform K assumption. Future work should incorporate transient scenarios and water quality, aligning with calls for data-driven approaches in Nigeria [3]. Management Implications: Prioritize 60–80 m boreholes (360–500 m^3/day) in Very High zones; rehabilitate wells in Moderate zones; promote rainwater harvesting in Low zones. Regular monitoring and policy enforcement are essential [4].

4 CONCLUSIONS

This study successfully developed and applied an integrated framework combining geophysical surveys (15 VES points), pumping test analysis, GIS-based multi-criteria decision analysis using the Analytic Hierarchy Process (AHP), and steady-state numerical groundwater flow modeling with ModelMuse/MODFLOW for Otukpo and its environs in Benue State, North Central Nigeria. Key findings include hydraulic conductivity values ranging from 7.59 to 54.09 m/day (mean ≈ 29.35–30 m/day) and transmissivity of 145.83–1,167.50 m^2/day (mean 740 m^2/day), derived from VES data inversion in IPI2WIN and validated against pumping tests (strong correlation, $R = 0.998$). The GIS-AHP weighted overlay classified the 52 km^2 study area into groundwater potential zones as follows: 35.5% very high, 40.7% high, 17.5% moderate, and 6.2% low. The three-layer conceptual MODFLOW model achieved excellent calibration with a perfect 0.00% water balance discrepancy, simulating groundwater heads of 137.5–155.0 m (mean 142.5 m) and modest drawdowns of 0.5–1.6 m under current abstraction scenarios (15 wells at 360 m^3/day each). Zonal statistics and ANOVA confirmed significant variations in simulated heads across GWP zones ($F=395.2$, $p<0.001$). This represents the first application of ModelMuse/MODFLOW in the area and demonstrates the value of coupling static GIS-based potential mapping with dynamic numerical simulation in a heterogeneous sedimentary aquifer system within the Lower Benue Trough. The results highlight substantial sustainable groundwater development potential, particularly in the central and eastern very high potential zones, where targeted boreholes (60–80 m depth, 360–500 m^3/day) can be prioritized while maintaining ecological balance with natural discharge to streams. The integrated approach provides a robust, replicable, and cost-effective methodology for sustainable groundwater management in data-scarce regions of Nigeria and similar sedimentary basins. Future work should extend the model to transient simulations, incorporate water quality and contaminant transport modules, and include denser monitoring networks for enhanced calibration and climate change scenario analysis. Overall, this research offers critical scientific support for evidence-based policy, infrastructure planning, and long-term water security in Otukpo and comparable environments.

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