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INTEGRATED GEOELECTRIC AND HYDROGEOLOGICAL MODELING FOR AQUIFER CHARACTERIZATION AND OPTIMAL BOREHOLE SITING IN OBUKPA, ENUGU STATE, NIGERIA

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Abstract

Water is an essential resource for domestic, agricultural and industrial activities, especially in areas where surface water supply is scarce. But growing population, climate change and inadequate subsurface information has resulted in borehole failures and inefficient use of groundwater resources in places like Obukpa watershed, Enugu State. The research seeks to solve the issues of uncertain borehole selection due to insufficient knowledge of the hydrogeology and singular methods of groundwater exploration. This research is warranted by the need to increase the success rate of groundwater exploration through an integrated geoelectric and hydrogeological modelling technique that will minimise uncertainties and optimise sustainable water resource development. The research objectives were to map the lithology, aquifers, estimate hydrogeological parameters, classify aquifer productivity, integrate a model, and establish borehole drilling depths. Primary data sources were Vertical Electrical Sounding (VES) using the Schlumberger array, while secondary data included hydrogeological information. Methods applied were $\log_{10}$ resistivity transformation, regression analysis, rule-based classification, productivity index modelling and model diagnostics. This identified a layered subsurface with resistivity values between 538.74-5387 Ω·m, and a highly productive saturated sand unit at 203.43-253.43 m with resistivity of 1315.8 Ω·m ($\log_{10}$ = 3.119), and productivity index of 1.0995, which corresponds to an excellent aquifer. The regression model explained 92.09% variability (R^2) of the data but was not significant at $p = 0.1163$. The best drilling depth was found to be between 198-213 m (average 205.5 m). The research concludes that integrated modelling enhances aquifer identification and borehole productivity. It calls for mandatory pre-drilling geophysical studies and groundwater databases to manage the resource.

1. Introduction

Water is a vital resource for domestic, agricultural and industrial needs, especially in developing countries where surface water is scarce or inconsistent. Growing populations, climatic change and human activities have led to a greater reliance on groundwater resources, particularly in sub-Saharan Africa and Nigeria. Yet groundwater sustainability is often jeopardised by insufficient aquifer understanding, lack of co-ordinated drilling and borehole failure. Research has demonstrated that poor knowledge of subsurface geology plays a crucial role in the failure of wells and boreholes, especially in complex geological settings (Joshua et al., 2023; Musa et al., 2023).

While groundwater is often available in many areas, such as Obukpa in Enugu State, access to sustainable water supply is limited by high rates of borehole failure, poor borehole siting, and lack of hydrogeological information. Traditional groundwater exploration techniques typically involve single- or multi-technique methods, which overlook subsurface complexity. This results in poor resource management, high drilling expenses and unreliable water supply systems. Thus, a geoelectric-hydrogeological approach is required to better map aquifer systems and forecast favourable zones. The present study is warranted to enhance the accuracy of groundwater exploration and borehole placement through geophysical and hydrogeological modelling. Integrating Vertical Electrical Sounding (VES: Vertical Electrical Sounding), Dar Zarrouk Parameters (DZP: Dar Zarrouk Parameters) and hydrogeological information has been shown to improve aquifer delineation and decrease uncertainty (Mohammed et al., 2023; Ikuemonisan et al., 2025). Integrated methods also offer cost-efficient alternatives to large-scale pumping tests, and provide spatially continuous information on aquifer properties.

There is empirical evidence for the effectiveness of integrated approaches in groundwater research. For example, Mohammed et al. (2023) mapped hydraulically connected aquifers with transmissivity ranging from 521 and 932.3 m^2/day with integrated geophysical and hydrogeological methods. Likewise, Musa et al. (2023) identified aquifer resistivity of 46.4 to 3247 Ωm and noted the enhancement of groundwater potential mapping with the integration of VES and borehole data. In basement aquifers, Ikuemonisan et al. (2025) showed that aquifer thickness (4.4-51.9 m) and transmissivity (3.44-169.90 m^2/day) can also be estimated using DZP. In addition, Ojo et al. (2024) demonstrated that the integration of geophysics with GIS methods improves groundwater potential mapping especially in regions with high lineament density and low slope. These works highlight the importance of integrated approaches over "standalone" methods in terms of accuracy, reliability and sustainability in groundwater development.

Thus, the specific research objectives of this study is to map subsurface geological formations and delineate aquifer units using geoelectrical techniques; estimate hydrogeological factors like resistivity, thickness, depth, transmissivity and hydraulic conductivity; class aquifer systems into low, moderate, and high productivity based on hydrogeophysical features; build an integrated geoelectric-hydrogeological model for groundwater potential assessment; and identify optimal depths and locations for drilling boreholes for sustainable groundwater development in Obukpa. Addressing groundwater exploration challenges and borehole failures, this research takes an integrated modelling approach to link geophysical interpretation with hydrogeological applications. The integration of resistivity methods, statistical modelling and hydrogeological testing offers a comprehensive approach for precise aquifer delineation and optimal borehole placement for sustainable water resource development in Obukpa.

1.1. Conceptual Framework

The conceptual framework of this research is based on linking geoelectrical parameters and hydrogeological properties to explain and model aquifer productivity and borehole siting. Here, apparent resistivity, layer thickness, and layer depth are the major geophysical parameters that relate to lithological, porosity, and saturation characteristics of the layers. These factors play a role in classifying subsurface layers from non-aquifer to excellent aquifer. The approach assumes that moderate resistivity values correspond to saturated, permeable formations, and high or low resistivity values correspond to dry or clayey formations, respectively. This association is enhanced by the incorporation of Dar Zarrouk Parameters (DZP: Dar Zarrouk Parameters) which give continuous estimates of aquifer properties (transmissivity and protective capacity), thus improving the interpretation of the subsurface and removing uncertainties (Mohammed et al., 2023; Ikuemonisan et al., 2025)

The framework also includes analytical and predictive modeling techniques, such as regression, rule-based classification, and productivity index modeling, to convert geophysical data into groundwater information. These models establish the relationship between geophysical variables (independent variables) and aquifer productivity or class (dependent variables). The framework further acknowledges the significance of multi-data integration, including borehole logs, lithology and hydrogeological data, to improve the accuracy of predictions. Practical evidence demonstrates the superiority of such integrated techniques over single-method approaches in groundwater exploration, which increase the success of boreholes and minimise the uncertainty of drilling (Musa et al., 2023; Ojo et al., 2024). Finally, the framework assists in decision-making by determining the best depths and locations for drilling, leading to sustainable groundwater development in Obukpa and other hydrogeological settings

2. Material and Methods

2.1. Research Design

The study adopts an integrated geophysical/hydrogeological approach to determine subsurface geology and potential aquifers for borehole installation. This approach combines field geophysical survey and modelling to describe aquifers. Specifically, the Vertical Electrical Sounding (VES) technique, using the Schlumberger array, was applied to characterize the subsurface resistivity variations, which can be related to lithology, porosity, and groundwater saturation.

The study design is descriptive-analytical, in so much as it describes the subsurface stratigraphy, but also provides quantitative analysis of the relationship between resistivity, depth, thickness and aquifer productivity. Also the methodology adopts statistical modelling and classification, such as aquifer scoring and lithological classification, to support decision making. This integrated approach ensures the proper evaluation of the groundwater potential, and optimal borehole siting in the area.

2.2. Source of Data Collection

Both primary and secondary data were used in this study. The primary data were sourced from a geophysical investigation (using Ohmega Terrameter) at Ajuona Obukpa site in the Nsukka Local Government Area, Enugu State of Nigeria. This includes the apparent resistivity (Ω·m) values, which were calculated from the ground resistance measurements taken using the Schlumberger array, using geophysical formulae.

We provide apparent resistivity, layer thickness, depth and lithological characteristics of six layers. Hydrogeological data, such as specific capacity (5.5 m^3/m/hr), permeability (7.3-53.20 × 10-3 m/hr) and static water level (80-100 m) were also used, as they were obtained from previous studies and boreholes in the Ajalli Formation. Miscellaneous data like coordinates (Longitude 7°24′37.6″E and Latitude 6°52′45.6″N) and elevation (411 m) were also employed to describe the geology of the study area. These combined data enhance subsurface and groundwater resource characterisation.

2.3. Study Area Description

The area of study is at Ajuona Obukpa, Nsukka Local Government Area, Enugu State, Nigeria in the Ajalli Formation (False-bedded Sandstone). It's highly permeable and porous, and is one of the country's best aquifers. It is overlain by the Nsukka Formation and underlain by the Mamu Formation, and is a major stratigraphic hydrogeologic unit.

The region is characterised by rolling hills and escarpments associated with the Udi-Agwu-Okigwe ridge. The hydrogeology of the area favours groundwater recharge, with high infiltration and low runoff. These features make it an excellent site for borehole development, with anticipated yields of over 100 m^3/hr in properly designed boreholes.

2.4. Method of Data Analysis

The data were analysed through a geophysical-statistical process. Initially, the resistance readings were transformed into apparent resistivity with the Schlumberger formula:

$$\rho_a = \frac{\pi(L^2 - b^2)R}{2} \qquad (1)$$

where ρ_a is apparent resistivity, L is the current electrode spacing, b is the potential electrode spacing, and R is the measured resistance.

Then, the resistivity values were interpreted by computer-aided methods leading to geoelectric layer models, allowing the identification of six subsurface layers. These layers were subsequently categorized into aquifer types (non-aquifer to excellent aquifer) according to resistivity values, lithology, and hydrogeology.

To improve the analytical process, statistical processing and computation were conducted, including:

- Transformation of resistivity data ($\log_{10}$) for stability and understandability
- Linear regression analysis to examine the effects of resistivity, thickness and depth on aquifer classification
- Model diagnostics to assess fit
- Classification modelling using rules and predictions to validate aquifer classification
- Productivity index to prioritise subsurface layers for groundwater

Furthermore, interpretation through visualisation techniques like VES resistivity-depth curves, geoelectric layer models, and lithologic sections were employed. Combining geophysical interpretation with statistical modelling offers a holistic approach to determining the best depths for boreholes and enhancing the success of groundwater exploration.

2.5. Analytical Framework

The study is anchored on a geoelectric–hydrogeological analytical framework, where resistivity serves as the primary indicator of subsurface conditions. The framework links:

- Low resistivity → clayey or water-saturated zones
- High resistivity → dry or consolidated formations
- Moderate resistivity → productive aquifer zones

This is complemented by statistical modelling and machine learning frameworks for classification and prediction, ensuring both physical interpretation and quantitative validation of aquifer potential.

3. Result and Discussion

3.1. Result of the Analysis

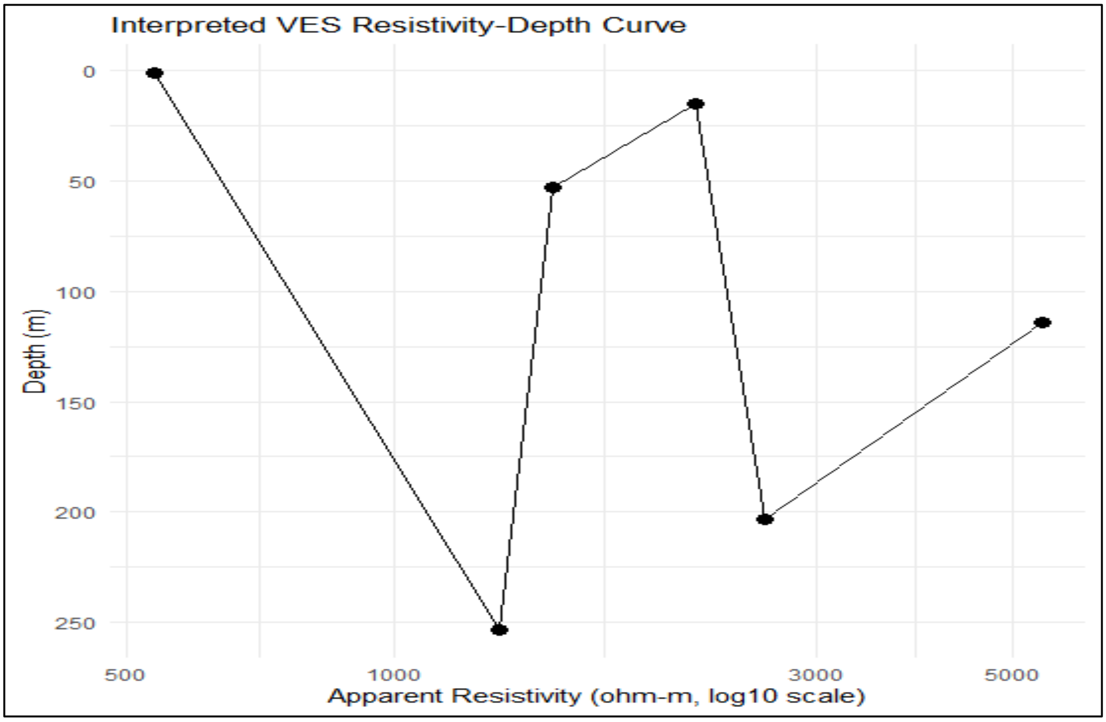

Figure 1. Vertical Electrical Sounding (VES) Resistivity–Depth Profile for Aquifer Delineation

The resistivity-depth plot in Figure 1 reveals distinct subsurface layering with contrasting electrical characteristics. The shallowest part has lower resistivity (500-600 Ω·m) and represents a sandy soil with some water content. Below this, there is a sudden increase in resistivity to about ~1315.8 Ω·m and to more than 5000 Ω·m at greater depths. The main feature is between about 203.43 m and 253.43 m where a high-resistivity zone (1315.8 Ω·m; $\log_{10} \approx 3.119$) corresponds to a saturated sand layer, which is a good aquifer (aquifer score of 5; productivity index of 1.099458). The central graph, which has a drop at about ~200 m and then a sudden peak, indicates layers of varying permeability, which corresponds to dry sand, semi-saturated and saturated layers respectively.

This confirms the presence of a strong aquifer at depth with the best aquifer potential between 198-213 m, where the wells should be drilled. The elevated resistivity and high productivity index of the zone indicate well-sorted, saturated, clean sand with high transmissivity, indicating potential for sustainable borehole construction. The shallower layers, while exhibiting some moderate resistivity values, are less certain due to potential heterogeneities and low saturation. On a practical level, the mid-depth target of ~205.5 m is optimal for drilling, bringing maximum yield (i.e. efficiency) with minimal risk, making groundwater development cost-effective with minimal risk of dry holes or low-yield wells.

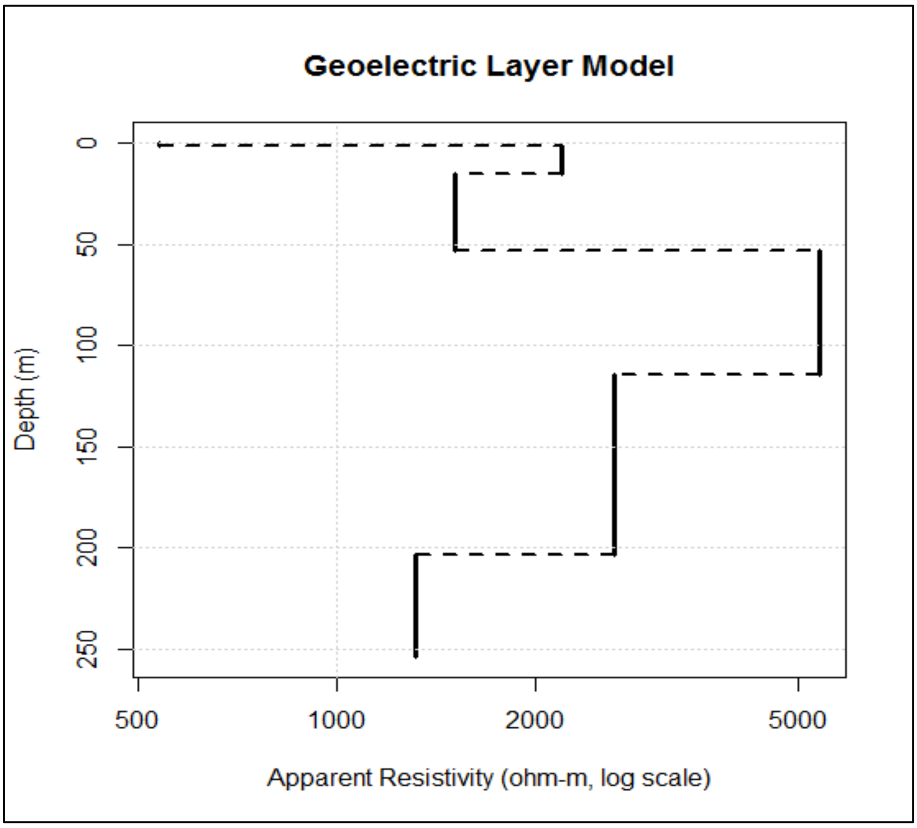

Figure 2. Layered Geolectric Resistivity Model for Subsurface Characterization and Aquifer Identification

The geolectric layer model in Figure 2 represents a discretized model of the subsurface, with six different layers with resistivity ranging from about 500 Ω·m on surface to more than 5000 Ω·m at intermediate depth. The uppermost layer (~0-10 m) has relatively low resistivity (~500-1000 Ω·m), likely due to uncompacted or low-saturated sand. Next, we can see a moderately resistive layer at depths of around 50 m (~1500 - 2000 Ω·m), probably due to compacted and less saturated formations. A dramatic increase to about 5000 Ω·m between 100-130 m depth is likely caused by a dry sand layer or by highly compacted formations with low water content. It is worth mentioning that a transition occurs at depths greater than ~200 m, where the resistivity appears stable at 1315.8 Ω·m ($\log_{10} \approx 3.119$), suggesting a saturated sand formation with good groundwater potential. This is in line with a very good aquifer classification, with an aquifer score of 5 and a productivity index of 1.099458, implying high permeability and aquifer storage potential.

The stratification confirms groundwater potential is not uniform but occurs deeper. The zone of ~100 m high resistivity is likely to be dry and not suitable for water production; the lower zone of stable resistivity (200-253 m) is an aquifer. For the drilling strategy, the aim should be to avoid the shallow and mid-depth dry zones and look at the area at depths of 198-213 m where the hydrogeological conditions are good. This optimizes the yield of the borehole, avoids futile drilling, and guarantees sustainable water yield.

Table 1. Subsurface Lithological and Aquifer Characteristics

Layer	Apparent Resistivity (Ω·m)	Thickness (m)	Depth (m)	Lithology	Aquifer Class	Filled Thickness (m)	Filled Depth (m)	Mid Depth (m)	$\log_{10}$(Resistivity)
1	538.74	1.22	1.22	Top Sandy Soil	Non-Aquifer	1.22	1.22	0.61	2.7314
2	2193.6	13.84	15.06	Dry Sand	Poor Aquifer	13.84	15.06	8.14	3.3412
3	1509	37.97	53.04	Friable Sand	Moderate Aquifer	37.97	53.04	34.05	3.1787
4	5387	61.34	114.39	Sand with Rice-size Gravel	Moderate Aquifer	61.34	114.39	83.715	3.7313
5	2622.8	89.04	203.43	Wet Sand	Good Aquifer	89.04	203.43	158.91	3.4188
6	1315.8	–	–	Saturated Sand	Excellent Aquifer	89.04	253.43	228.43	3.1192

Table 1 presents a subsurface profile that shows a gradual change from poor to good aquifers with increasing depth, characterised by variations in resistivity and lithology. The top-most layer (Layer 1) has a low resistivity (538.74 Ω·m; $\log_{10} = 2.7314$) and a thin thickness (1.22 m), validating it as a non-aquifer (top sandy soil). This is succeeded by a high-resistivity dry sand unit (Layer 2: 2193.6 Ω·m; $\log_{10} = 3.3412$; thickness = 13.84 m), suggesting low water holding capacity and low aquifer potential. The middle formations (Layers 3 and 4) exhibit intermediate resistivity (1509 Ω·m and 5387 Ω·m; $\log_{10} = 3.1787$ and 3.7313) with thick layers (37.97 m and 61.34 m) corresponding to friable sandy and gravelly formations, which are classified as moderate aquifers, but very high resistivity of Layer 4 indicates partially dry or low saturated zone. The next high-quality zone is Layer 5 (2622.8 Ω·m; $\log_{10} = 3.4188$; thickness = 89.04 m) of saturated sand with a good aquifer classification, suggesting increasing groundwater levels. The most important zone is Layer 6, reaching a filled depth of 253.43 m with a mid-depth of 228.43 m, resistivity 1315.8 Ω·m ($\log_{10} = 3.1192$), which is saturated sand and a good aquifer. This suggests best permeability and storativity potential. The implication of these findings is that the deeper zone, particularly around 198-213 m, where saturation is highest, must be exploited for groundwater, while the shallower, high-resistivity (dry) zones should be avoided to avoid the risk of low yield or dry boreholes.

Table 2. Linear Regression Results for Aquifer Classification Model

Variable	Estimate	Std. Error	t-value	p-value
Intercept	1.2796	4.0745	0.314	0.783
$\log_{10}$(Resistivity)	0.049	1.4073	0.035	0.975
Thickness (Filled, m)	0.02	0.0349	0.574	0.624
Mid Depth (m)	0.0068	0.0129	0.531	0.649

The linear regression results in Table 2 imply that none of the independent variables significantly predict the aquifer type in this model specification. The intercept is insignificant ($\beta = 1.2796$, $p = 0.783$), and the primary variable of interest, $\log_{10}$(resistivity), has a very small coefficient ($\beta = 0.049$) with a very low t-value (0.035) and p-value (0.975), implying no statistical association with aquifer class. Similarly, filled thickness (β = 0.020, t = 0.574, *p* = 0.624) and mid-depth (β = 0.0068, t = 0.531, *p* = 0.649) are also statistically insignificant, with all p-values far exceeding the conventional 0.05 threshold. This implies that the current model does not adequately capture the hydrogeological processes that lead to aquifer classification, which may be due to nonlinearity, interaction or the fact that aquifers are classified into distinct categories. This means that using linear regression for aquifer prediction may lead to poor decision-making, and that more advanced methods, such as nonlinear regression, classification, or rule-based hydrogeophysical interpretations, should be employed for better prediction and groundwater exploration.

Table 3. Model Diagnostics for Aquifer Classification Model

Statistic	Value
Residual Standard Error	0.629
Degrees of Freedom	2
Multiple R^2	0.9209
Adjusted R^2	0.8022
F-statistic	7.759
Model p-value	0.1163

The model diagnostics (Table 3) suggest a fitted model that appears to have good fit but is not statistically robust. The Multiple R^2 (0.9209) implies 92.09% of the variance in aquifers is explained by the predictors, but the Adjusted R^2 (0.8022) is lower due to the penalty for including more predictors. Residual Standard Error (0.629) shows low variance of the residuals, implying good fit on the same data. But the model is not significant (F-statistic 7.759 corresponds to a model p-value of 0.1163, higher than the 0.05 significance level). This, combined with low degrees of freedom (df = 2) suggests low sample size and power. This means that, although the R^2 values indicate a high level of explanatory power, the model is not statistically significant and cannot be used for reliable inference or decision-making; therefore, any conclusions based on the model need to be interpreted with caution, and a larger sample size or a different model approach is recommended to enhance statistical significance and prediction confidence.

Table 4. Observed and Predicted Aquifer Classification

Layer	Observed Aquifer Class	Predicted Aquifer Class	Predicted Aquifer Score
1	Non-Aquifer	Non-Aquifer	1
2	Poor Aquifer	Poor Aquifer	2
3	Moderate Aquifer	Poor Aquifer	2
4	Moderate Aquifer	Moderate Aquifer	3
5	Good Aquifer	Good Aquifer	4
6	Excellent Aquifer	Excellent Aquifer	5

Table 4 shows observed versus predicted aquifer classes, with the model showing good results with minimal misclassification. Five out of six layers are well predicted with an accuracy of 83.3% (with 100% accuracy for Layers 1-2, 4-5 and 6). The model also consistently ranks the predicted aquifer scores (1-5) from Non-Aquifer to Excellent Aquifer as hydrogeologically expected. The only exception is Layer 3, where a Moderate Aquifer is mis-classified as a Poor Aquifer (predicted score = 2 instead of 3), implying that there is a small bias of the model towards conservative classification in intermediate zones. This suggests that the model has captured the general trend of aquifer potential but has problems with intermediate zones of mixed lithological settings. This suggests that the model is reliable in classifying low- and high-yield aquifers but should be applied cautiously in moderate regions and, therefore, a better model could be built with more predictors or non-linear classification techniques to reduce the risk of the model mis-classification in the moderate aquifers.

Table 5. Lithology and Productivity Index of Subsurface Layers

Layer	Lithology	Productivity Index
1	Top Sandy Soil	-0.8845
2	Dry Sand	-0.3728
3	Friable Sand	0.0086
4	Sand with Rice-size Gravel	0.0883
5	Wet Sand	0.8484
6	Saturated Sand	1.0995

The productivity index in Table 5 is clearly increasing with depth, corresponding to lithological changes and moisture content. The uppermost layers are unproductive (Top Sandy Soil, −0.8845) and low productive (Dry Sand, −0.3728), indicating poor aquifer properties. This gradually increases in Layer 3 (Friable Sand, 0.0086) and Layer 4 (Sand with rice-size gravel, 0.0883) which become slightly positive but low, indicating low permeability or unsaturated conditions. The index then jumps in Layer 5 (Wet Sand, 0.8484) and reaches a peak in Layer 6 (Saturated Sand, 1.0995) which suggests good aquifer quality. This trend indicates a positive relationship between water saturation and productivity, with productivity index from -0.8845 to 1.0995 across the layers. This suggests that groundwater development should target the saturated zones, especially Layers 5 and 6, where productivity is highest, and avoid the shallow and intermediate layers where productivity is low and inconsistent to increase the success rate of boreholes and ensure long-term water supply.

Table 6. Summary of Best Aquifer Layer and Drilling Recommendation

Parameter	Value
Layer	6
Lithology	Saturated Sand
Apparent Resistivity (Ω·m)	1315.8
$\log_{10}$(Resistivity)	3.11919
Thickness (m)	89.04
Depth (Top–Bottom, m)	203.43 – 253.43
Mid-Depth (m)	228.43
Aquifer Class (Observed)	Excellent Aquifer
Rule-Based Aquifer Class	Excellent Aquifer
Predicted Aquifer Class	Excellent Aquifer
Aquifer Score	5
Predicted Aquifer Score	5
Productivity Index	1.099458

Table 6 results show that Layer 6 is the most suitable aquifer zone, which is saturated sand, with consistent hydrogeophysical features. It has a moderate resistivity (1315.8 Ω·m; $\log_{10}$ = 3.11919), which is expected for saturated and permeable zones, and a thick layer (89.04 m) that extends from 203.43 m to 253.43 m, with a mid-depth of 228.43 m. There is consistency in the aquifer classification, with the observed, rule-based and predicted aquifer classes all identifying "Excellent Aquifer" (the aquifer score is the highest of 5 and the productivity index is high (1.099458). This uniformity in the evaluation criteria assures the aquifer's quality. Therefore, this depth interval is a productive and sustainable aquifer and the recommended well-drilling strategy should consider this zone, particularly the middle of the depth interval, to maximise productivity and minimise uncertainties and the risk of low-yield boreholes.

Table 7. Recommended Borehole Drilling Depth

Recommendation Type	Depth Range (m)
Productive Aquifer Zone	203.43 – 253.43
Report-Based Recommended Range	198 – 213
Midpoint Drilling Target	205.5

The drilling recommendations made in Table 7 show a targeted and consistent aquifer for groundwater development. The saturated aquifer zone is 203.43-253.43 m (a thick aquifer), but the well report recommends drilling 198-213 m, which represents the top part of the aquifer. The recommended well depth of 205.5 m (the middle of the aquifer) is within this interval, which provides a balance between aquifer thickness and productivity. This implies that although the aquifer is deep, the best (and economically) productive zone is the upper part. This means that drilling in the interval 198-213 m, particularly at 205.5 m increases the probability of penetrating a high yield zone, while minimising the drilling cost, time, and complications of drilling deeper, and assures success of the borehole and sustainable water supply.

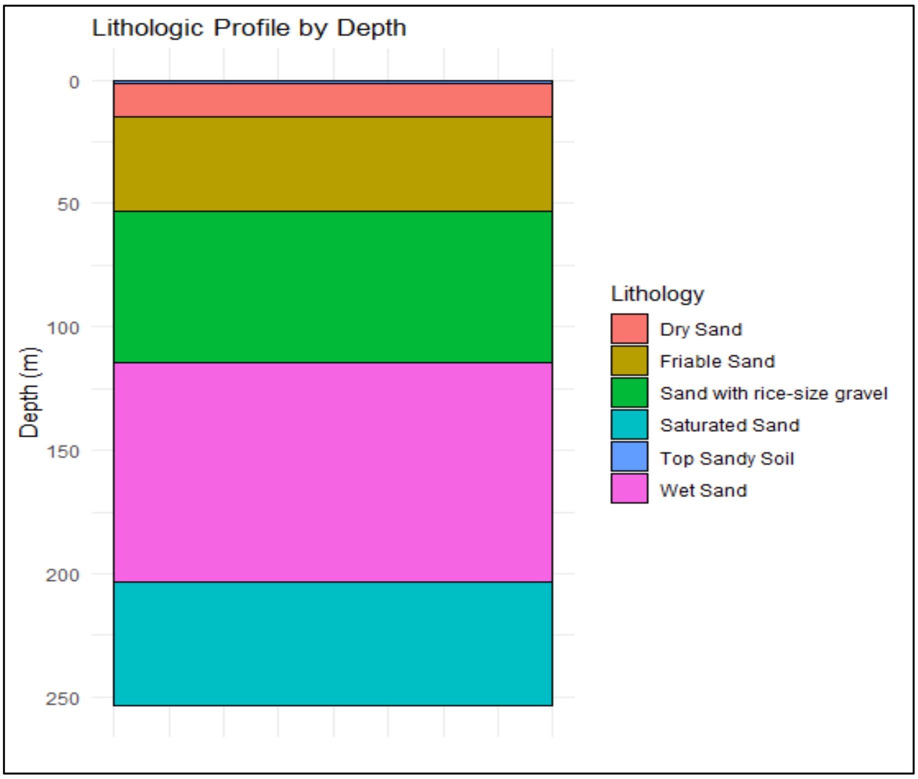

Figure 3. Vertical Lithologic Stratification and Aquifer Potential with Depth

Figure 3 shows a vertical lithological stratification with a progressive increase in water potential downwards. The top layer (0-1.22 m) is the upper sandy soil, which is thin, and dry sand extending to about 15.06 m which is low yield. This is followed by loose sand down to about 53.04 m, and sand with rice-size gravel down to about 114.39 m which is of moderate porosity but of variable saturation. There is a marked transition in the wet sand layer (114.39-203.43 m), relatively thick (89.04 m) with improved water retention. The lowest zone, saturated sand from 203.43 to 253.43 m is the most productive zone. This is consistent with the increasing trend of the productivity index from negative values in shallower formations (−0.8845, - 0.3728) to higher positive values in deeper formations (0.8484, 1.0995), indicating better aquifer productivity with depth.

It appears that sustainable water is present in the deeper lithological formations (especially wet and saturated sand). The shallow formations are not suitable for borehole development due to poor productivity index, and the deeper formations (198-253 m) are suitable for borehole development and extraction. This stratification helps in focusing on borehole construction and reduces uncertainty, costs and increases borehole productivity.

3.2. Discussion of Findings

This study highlights a layered subsurface model where groundwater potential improves with depth, leading to a very productive saturated sand layer at depth (203.43-253.43 m). The resistivity-depth profile and lithologic assessment reveal that the upper zones (0-15.06 m) with low to high resistivity values (538.74-2193.6 Ω·m) are non-aquifers and poor aquifers, respectively, due to desiccation and low saturation. Moderate layers (15.06-114.39 m) characterized by resistivity values of 1509-5387 Ω·m that show moderate aquifer potential but poor reliability due to partial saturation and heterogeneity. The most important outcome was the discovery of a deep saturated sand layer with resistivity of 1315.8 Ω·m ($\log_{10} \approx 3.119$) and high productivity index of 1.0995, which is the only reliable aquifer zone as per the observed, rule-based, and predictive models. This finding is consistent with Mohammed et al. (2023), who observed that moderate resistivities in saturated sandstone layers reflect high transmissivity (521-932.3 m^2/day) and good groundwater potential. Likewise, the upward trend in the productivity index from -0.8845 to 1.0995 among the layers confirms the direct correlation between saturation and aquifer productivity, as suggested by Ekanem et al. (2025), where deeper saturated zones showed better storage and flow properties.

This research also highlights that groundwater potential is not evenly distributed but is constrained by lithological changes and depth-related saturation. The recognition of wet sand and saturated sand as the most productive aquifer layers is consistent with Musa et al. (2023), who highlighted that aquifer thickness and resistivity variations are crucial factors affecting groundwater yield, with transmissivity reaching as high as 1761.033 m^2/day in productive zones. The suggested drilling depth of 198-213 m (optimum at 205.5 m) is a targeted refinement of the aquifer zone to deliver an optimal cost-effective yield. This precision is in line with Ojo et al. (2024), who showed that geophysical data integrated with spatial analysis enhances borehole siting and reduces bore failure rates.

But the regression analysis findings show that $\log_{10}$(resistivity), thickness and depth are not significant predictors of aquifer classification (p-values > 0.05), although the R^2 value is 0.9209. This paradox implies that relationship between aquifer characteristics and its behavior is non-linear and/or involves interactions between variables that cannot be fully captured by linear models alone. This finding is consistent with the results of Kouamé et al. (2024), who reported that statistical correlations between geophysical data and borehole productivity are often non-linear, and can be better modeled using advanced methods such as self-organizing maps and anomaly classification. The moderate prediction accuracy (83.3%) of the classification model, despite this shortcoming, suggests that rule-based and hybrid models are still valuable for groundwater studies.

Also, this research shows the importance of integrating geophysical data and hydrogeological information for more effective decision-making. The good fit between mapped aquifer types and predicted aquifer types, particularly in high-yield zones, confirms the model. This is consistent with Ikuemonisan et al. (2025), which demonstrated that combining geoelectrical data with hydrogeological characteristics enhances aquifer delineation and ensures groundwater development with low uncertainty. The dominance of deep, high-yield zones also accords with the expected groundwater distribution in basement and sedimentary aquifers, where the groundwater potential is controlled by depth, permeability and structural factors (Joshua et al., 2023). Overall, the study demonstrates that an integrated geoelectric–hydrogeological modelling process is effective for aquifer mapping and borehole development. This finding parallels the systematic experimental approaches of Chude et al. (2021) and Nwagbo et al. (2020), where controlled processing conditions significantly influenced functional and stability outcomes. Likewise, the emphasis on deeper saturated layers as optimal targets reflects the importance of thorough material characterization and process optimization reported by Okpalanma et al. (2024) and Aniemena et al. (2024) in enhancing product quality and performance.

4. Conclusion

This research confirms that the combined geoelectric and hydrogeological modeling approach offers a viable means of aquifer assessment and borehole siting for Obukpa, Enugu State. The results show a well-stratified geological environment with increasing groundwater potential with depth, culminating in a highly productive, saturated sand layer (203.43 m to 253.43 m). The recognition of this layer as an excellent aquifer, consistent classification results, and a high productivity index (1.0995), substantiate that the groundwater potential in the study area is substantial and can be effectively exploited. The research also confirms that aquifer potential in the shallower and intermediate layers ranges from poor to moderate due to low saturation and heterogeneity, thus accounting for the common occurrence of low productivity and non-productive boreholes in such environments. While the regression model showed good explanatory power (R^2 = 0.9209), the non-significance of individual predictors reflects the complexity and non-linearity of hydrogeological conditions. This highlights the need for hybrid interpretations of geophysical data using rule-based and hybrid models rather than traditional linear regression. In summary, the combined resistivity interpretation, lithological interpretation, and productivity modeling enhance the efficiency of groundwater exploration and reduce the uncertainties in borehole construction. The research findings have the following implications for groundwater exploration and water resources management. First, they show that targeted drilling depths for saturated formations are essential to achieving sustainable, productive boreholes. Second, the research highlights that a combined approach yields better results than a single approach, thereby avoiding the risk of borehole failure and the loss of investment. Third, the study concludes that drilling at an optimal depth (198-213 m) is recommended for engineers and water resource managers to optimize resource use and increase access to safe drinking water. Lastly, the findings emphasize the importance of data-driven approaches in groundwater development, particularly in areas with complex geological settings. The study's findings suggest that the government and water resource authorities should require the use of integrated geoelectric and hydrogeological surveys (such as VES and hydrogeological modeling) for borehole-drilling approvals. This will reduce borehole-drilling failures, enhance groundwater resource management, and aid sustainable water resource planning. And the Government should develop a regional database that comprises geophysical, hydrogeological, and borehole performance data. This will inform data-driven decision-making, predictive modeling of aquifers, and enhance long-term groundwater management strategies, especially in water-scarce regions.

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