

Quantitative Assessment of Aquifer Transmissivity and Vulnerability Using Dar Zarrouk Parameters from Schlumberger Resistivity Soundings in the Borikiri Area, Niger Delta

Tom Cyprian N.¹; Warmate Tamunonengiyeofori²; Tamunosiki Dieokuma³

¹Department of Agricultural and Engineering, Rivers State University, Port Harcourt, Rivers State

²Geostrat International Services Limited, Rivers State, Nigeria

³Department of Physics, Federal University Otuoke, P.M.B 126 Bayelsa State, Nigeria

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Abstract: Hydrological estimates were derived from geophysical parameters to assess aquifer proficiency in the Borokiri area of the Niger Delta. Schlumberger vertical electrical soundings were conducted with a maximum current electrode spread (AB) of 400m, generating HK-type model curves. Dar Zarrouk parameters extracted from the geoelectric data were converted to relevant hydrological properties, including hydraulic conductivity and transmissivity. The study reveals highly prolific aquifer zones with resistivity values exceeding 1000 Ωm and modelled transmissivity values of 2125 m^2/day , classified as Krasny Class I magnitude—indicating regional groundwater importance. Formation factor analysis, based on established porosity and cementation values within the Benin Formation, enabled quantitative estimation of hydraulic conductivity. The geoelectric sections delineated four subsurface layers, with the third layer (18.5m thick at 24.8m depth) identified as the primary freshwater aquifer, underlain by a fourth layer with extremely low resistivity (1.1 Ωm), interpreted as a saline aquifer resulting from saltwater intrusion. Calculated longitudinal conductance values of less than 0.1 siemens indicate poor overburden protective capacity, rendering the aquifer vulnerable to surface contamination. These findings demonstrate that while the Borikiri area hosts high-yield freshwater aquifers suitable for regional water supply, the absence of protective clay layers necessitates careful contamination management. The study confirms the efficacy of integrating Dar Zarrouk parameter analysis with conventional resistivity sounding for quantitative aquifer evaluation in complex deltaic environments.

Keywords: Aquifer Transmissivity; Hydraulic Conductivity; Dar Zarrouk Parameters; Schlumberger Sounding; Saline Water Intrusion; Niger Delta; Groundwater Vulnerability; Electrical Resistivity.

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I. INTRODUCTION

Groundwater resources in coastal regions of southern Nigeria are a major source of domestic, industrial and agricultural water supply. In the Niger Delta, aquifer systems are often thick and permeable, yet they are highly susceptible to contamination from saline water intrusion, tidal mixing and anthropogenic inputs [19]. Saline encroachment remains a persistent challenge in deltaic aquifers due to the hydraulic connectivity between freshwater lenses and adjacent estuarine or marine water bodies. Excessive pumping or prolonged dry periods can exacerbate lateral migration of saline water into freshwater zones, compromising water quality and undermining the sustainability of pumping [2], [3].

In regions with limited hydrogeological data, geophysical methods such as electrical resistivity surveying provide indirect yet reliable means of inferring lithology and fluid composition. Electrical resistivity varies with lithologic texture, pore-fluid salinity and water content, making it useful for groundwater delineation in unconsolidated coastal sediments [8], [5]. Vertical Electrical Soundings (VES) using a Schlumberger array have been widely applied to identify aquifer geometry and to classify subsurface layers according to their resistivity signatures.

Beyond qualitative interpretation, resistivity data can be transformed into hydrological estimates through Dar-Zarrouk parameters. Transverse resistance and longitudinal conductance integrate resistivity and layer thickness into

composite indices that correlate with transmissivity and aquifer protective capacity [11], [18]. These parameters provide practical insights into aquifer hydraulic behaviour, particularly in settings where conventional pumping test data are scarce or spatially limited.

The Borikiri area in Port Harcourt is characterised by intensive groundwater use and its proximity to the Bonny River estuary, raising concerns regarding saline intrusion and aquifer vulnerability. Despite the importance of groundwater in the region, comprehensive hydrogeological assessment has been limited, and available studies suggest heterogeneous subsurface conditions governed by coastal depositional processes [13]. Against this backdrop, this study uses VES and Dar-Zarrouk analysis to (i) delineate the subsurface geoelectrical structure, (ii) estimate hydraulic conductivity and transmissivity, (iii) evaluate aquifer protective capacity, and (iv) assess the potential influence of brackish water on deeper aquifer units.

➤ *Site Description and Hydrogeology:*

The study area lies in Borikiri, a district of Port Harcourt in Rivers State, southern Nigeria. Positioned on the eastern side of the Bonny River estuary, the area forms part of the coastal lowlands of the Niger Delta, with elevations generally less than 10 m above mean sea level. The terrain is flat to gently undulating, and extensive urbanisation has obscured many geomorphic features characteristic of coastal deposits.

The climate in the region is humid tropical, with annual rainfall exceeding 2000 mm and a distinct wet season from March to October. High precipitation enhances groundwater recharge, but poor surface drainage in low-lying areas can create perched water tables and influence salinity dynamics [7]. Tidal influence from the estuary can also extend groundwater salinity inland, especially during periods of low river discharge [17].

Surface deposits in Borikiri are dominated by unconsolidated sands of the coastal plain sands, commonly correlated with the Benin Formation. These sediments consist primarily of medium- to coarse-grained sands with varying amounts of clay and silt. The relatively high porosity and permeability of these units favour groundwater storage and transmission, but intermittent clay lenses can locally restrict vertical flow [1], [5].

Land use within the area is predominantly residential, with commercial activities and small-scale industrial operations. Groundwater is tapped through private and public boreholes, with little formal monitoring of quality or yield. The absence of extensive confining layers in parts of the coastal plain increases aquifer vulnerability to contaminant ingress from surface sources and saline water intrusion from tidal channels.

➤ *Hydrogeology:*

The hydrogeological framework of the Borikiri area reflects typical characteristics of coastal plain aquifer systems in the Niger Delta. The principal groundwater reservoir comprises thick, unconsolidated to weakly consolidated sands that host unconfined to semi-confined conditions at shallow depths. Minor clay and silt interbeds may occur but are often discontinuous, with limited confining effect [13], [17].

Recharge to the aquifer primarily occurs through direct infiltration of rainfall. Given the sustained high annual precipitation and sandy surface cover, infiltration rates are generally favourable. Groundwater flow is directed by local hydraulic gradients toward adjacent tidal channels and estuarine systems. In coastal settings, the balance between inland freshwater head and seawater pressure governs the position of the freshwater–saline interface [6], [2].

Aquifer transmissivity in coastal plain sands is typically high owing to the coarse texture and significant saturated thickness of the deposits. However, vulnerability to contamination and saline intrusion depends on the presence and continuity of low-permeability overburden. Zones with thin protective cover may allow rapid migration of surface pollutants or estuarine saline water into the aquifer [11], [7].

In resistivity surveys, freshwater-saturated sands are often associated with moderate to high resistivity, whereas saline-saturated zones exhibit lower resistivity due to enhanced ionic conduction. The identification of resistivity contrasts therefore provides an indirect yet reliable indication of groundwater quality variation and potential zones of saline influence.

In the Borikiri area, the hydrogeological conditions point to a productive yet vulnerable aquifer system. The integration of resistivity data with Dar-Zarrouk parameters offers a practical means of estimating transmissivity and protective capacity, which are key to informed groundwater development and management.

root-mean-square (RMS) error between observed and calculated apparent resistivity values, yielding a best-fit layered-earth model for each sounding location. Only models with acceptable misfit values were retained for further analysis.

Geoelectrical layers were interpreted by correlating resistivity ranges with likely lithologic units based on regional geological knowledge of the coastal plain sands. Low resistivity values were generally associated with clay-rich or saline-saturated zones, while moderate to high resistivity values were attributed to freshwater-bearing sandy formations. Layer continuity was assessed by correlating interpreted sections across adjacent sounding locations.

➤ *Basic Principles of Resistivity (DC) Method:*

Resistivity is measured by passing a current of known value in the ground by means of two electrodes (A, B) and measuring potential difference between two intermediate points in the ground using another two electrodes (M, N). As the electrode spread (A, B) increases, depth of probe increases, thereby, giving a vertical electrical sounding, VES. The equivalent soil resistivity, ρ_a , is calculated using the relevant formula (derive from ohms law):

$$\rho_a = \frac{\pi \Delta V}{4.I.MN} (AB - MN)(AB + MN)$$

Where,

ΔV = voltage

I = current

ρ_a = apparent resistivity

An aquifer can be characterized by its Transmissivity, its quantitative expression of the productivity of an aquifer and Coefficient of Storage, which determines its storage capacity [14]. The combination of thickness and resistivity into single, variables otherwise known as Dar Zarrouk parameters can be used as a basis for the evaluation of aquifer properties [12]. The Dar Zarrouk parameters consist of the Transverse Resistance (R_T) and Longitudinal Conductance (L_c). For a horizontal, homogeneous, and isotropic layer, the Transverse Resistance R_T (Ωm^2) is defined as:

$$R_T = \rho h \tag{1}$$

And the Longitudinal Conductance L_c (mho) is defined as:

$$L_c = h/\rho \tag{2}$$

Where h is the thickness of the layer (in metres) and ρ is the electrical resistivity of the layer in ohm-metres. But aquifer Transmissivity (T) is expressed as:

$$T = kh \tag{3}$$

Where k is the Hydraulic Conductivity (m/day). These relationship helps us infer the Transmissivity and Coefficient of Storage. Ioannis et al, proposed the following equation for k as shown below:

$$k(10^{-4}m/s) = 2.12f - 1.59 \tag{4}$$

Values of f , formation factor, which is dependent on the aquifer, [20] can be deduced from wyllie's relations, based on porosity value of 19.3 and cementation factor of 3 within the study area [3], [4], stated formation factor, f , of 2.61 within the Benin formation. Also, [4], stated the Formation factor of 7.6 at Amaoba, Within southern Nigeria with depth less than 200m.

[12], proposed a relationship between Transverse Resistance, R or longitudinal conductance and T

$$T = kR\sigma \tag{5}$$

Where

σ = Conductivity, R = Transverse Resistivity, and K = Hydraulic Conductivity

III. RESULTS

Raw field data was transferred to computer on completion of Field Work, A forward modelling subroutine was used to calculate the apparent resistivity (ρ_a) values, and a non-linear least-squares optimisation technique was used for the inversion routine.

Table 1 Showing Geoelectric Parameters and the Vulnerability Class (Henriet, 1975)

Vulnerability Classes	Geoelectrical Model Parameters		Dar Zarrouk Parameter
	Resistivity (ohm.m)	Thickness (meters)	Longitudinal Conductance (S) (siemens)
Very Low	< 10	> 25	> 2.5
Low	10 a 20	25 a 13	0.7 a 2.5
Moderate	20 a 40	13 a 10	0.3 a 0.7
High	40 a 100	10 a 5	0.1 a 0.3
Extreme	100 a 300	< 5	< 0.1

Table 2 Field Data for Point 2

AB/2(m)	MN	Resistivity
1	0.6	70.38729
1.5	0.6	47.81592
2	0.6	62.41012
3	0.6	65.46712
5	0.6	69.87421
7	0.6	251.611
7	2	72.7224
10	2	71.03151
15	2	119.5712
15	6	78.78888
20	6	83.89557
25	6	93.48827
30	6	932.58
40	6	233.1345
45	6	158.256
50	6	922.9653
55	6	157.8373
60	6	201.084
70	6	181.7333
80	6	247.5021
90	6	249.8231
90	10	25.3555
100	10	34.45365
120	10	13.54125
120	14	321.8724
150	14	397.7996
200	14	182.7929
200	30	54.12052

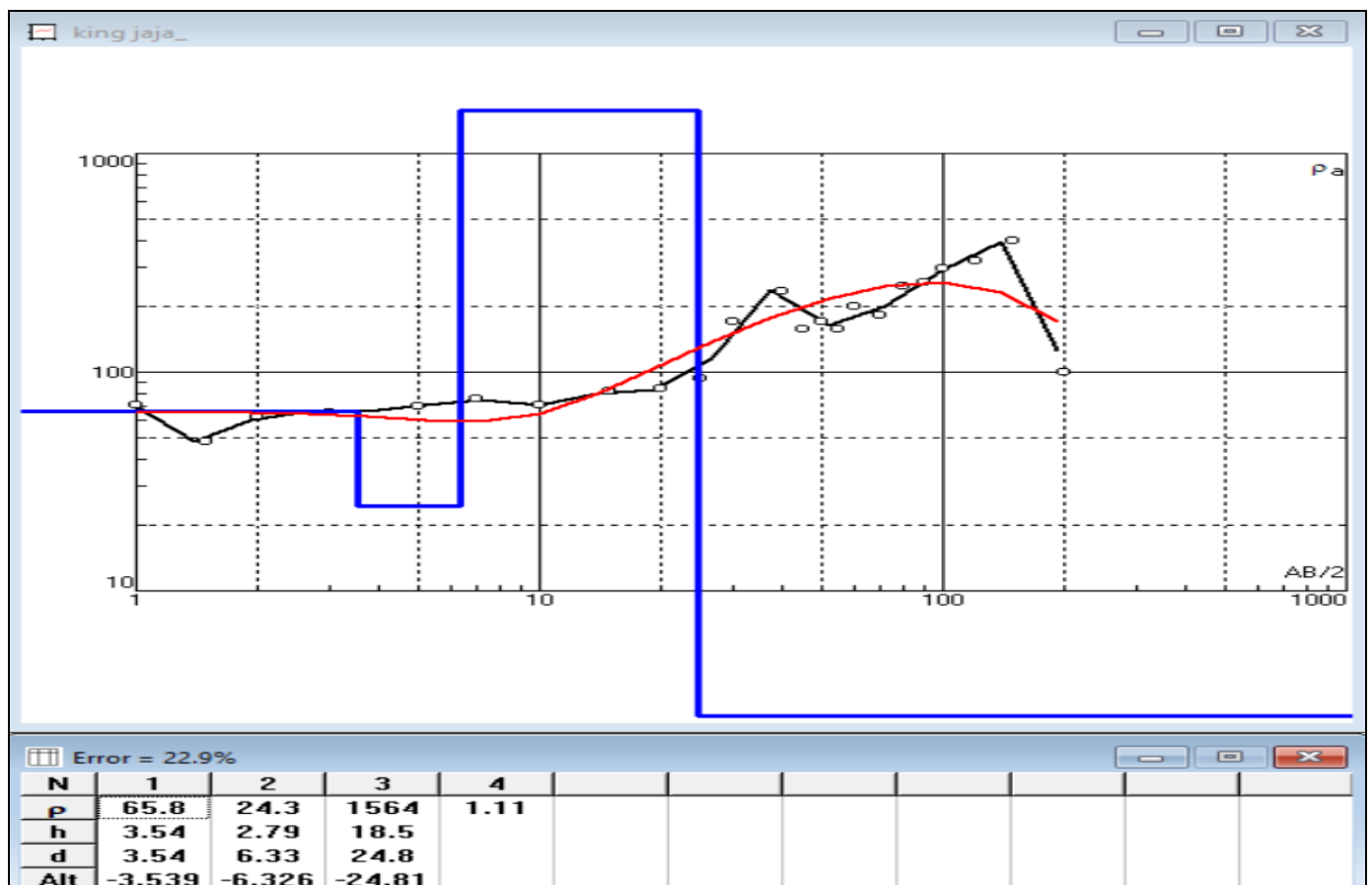


Fig 3 Showing Data and Model Curve

Table 3 Geoelectric Results for Point 1

Layers	Resistivity (ohm-m)	Thickness (m)	Depth (m)	Longitudinal Conductance (Siemens)	Transverse Resistance (ohm-m ²)	Lithology
1	65.8	3.54	3.54	0.537	232.9	Clayey
2	24.3	2.79	6.33	0.1148	67.7	Clayey
3	1564	18.5	24.8	0.011	28934	Sandy
4	1.11					Sandy

Table 4 Aquifer Properties, Point 1

Aquifer/layer	Resistivity (ohm-m)	Transverse Resistance (ohm-m ²)	Hydraulic Conductivity (10 ⁻⁴)m/s	Transmissivity (m ² /day)
3	1564	28934	13.3	2126

Assumed Formation Factor =7

IV. DISCUSSION

The geoelectrical results reveal a heterogeneous subsurface sequence typical of the coastal plain sands of the Niger Delta. The interpreted models generally indicate a multilayered system comprising a near-surface sandy overburden, intermediate sandy/clayey horizons, and deeper, more competent aquiferous units. Such vertical variability reflects the complex depositional history of deltaic environments, where alternating fluvial and marginal marine processes produce discontinuous sandy and clayey [13], [17].

The relatively high resistivity values observed within the principal aquifer units are consistent with freshwater-saturated coarse sands. In unconsolidated sediments, resistivity is strongly influenced by pore-water salinity and clay fraction; therefore, moderate to high resistivity values typically suggest low ionic concentration and limited clay content [8]. Comparable resistivity ranges for freshwater-bearing sands in the Niger Delta have been reported by [16] and more recently supported in subsequent coastal aquifer assessments [5]. The agreement between the present findings and earlier studies reinforces confidence in the interpretation of these units as productive freshwater aquifers.

Conversely, localized zones of relatively low resistivity at depth may indicate either clay-rich intercalations or possible saline influence. In coastal settings, distinguishing between these two causes requires careful consideration of layer geometry and regional hydrogeological context. Given the proximity of the study area to the Bonny River estuary, the possibility of brackish water intrusion cannot be excluded. Previous investigations in similar estuarine environments of southern Nigeria have documented resistivity reductions associated with saline mixing fronts [2], [7]. However, the absence of persistently very low resistivity values across multiple soundings suggests that any saline influence is likely localized rather than regionally extensive.

The computed Dar-Zarrouk parameters further clarify aquifer characteristics. Transverse resistance values derived for the principal sandy units indicate moderate to high transmissivity, reflecting favourable hydraulic conditions. In granular aquifers where lithology is relatively uniform, transverse resistance has been shown to correlate reasonably with transmissivity [18], [11]. The transmissivity estimates obtained in this study align with documented hydraulic

behaviour of the coastal plain sands, which are known for high permeability and substantial saturated thickness [1].

Longitudinal conductance values, used as an index of aquifer protective capacity, display spatial variability across the study area. Zones characterized by low longitudinal conductance suggest limited clay cover and, consequently, reduced attenuation capacity against vertical contaminant migration. Similar conclusions regarding aquifer vulnerability in the Niger Delta have been reported by Okiongbo and colleagues in geoelectrical vulnerability mapping studies, where thin overburden and sandy dominance were associated with weak protective ratings [16], [15]. The present findings are consistent with these earlier observations and highlight the need for careful groundwater management in densely urbanized coastal districts.

From a hydrogeological perspective, the results underscore the dual nature of the coastal plain aquifer system: it is both productive and potentially vulnerable. While the sandy formations provide favourable transmissivity for groundwater abstraction, the discontinuity of confining layers increases susceptibility to contamination and saline encroachment. This balance between productivity and vulnerability has been emphasized in recent regional groundwater studies across the Niger Delta [13], [17].

Overall, the integration of vertical electrical sounding with Dar-Zarrouk analysis has provided a coherent interpretation of subsurface conditions in the Borikiri area. The method proves effective for preliminary aquifer characterization in data-limited coastal environments. Nevertheless, confirmation through borehole lithologic logs and groundwater quality analyses would enhance interpretation reliability and allow clearer discrimination between clay-rich zones and saline-impacted layers.

V. CONCLUSION

Schlumberger vertical electrical sounding combined with Dar-Zarrouk parameter analysis has provided a coherent characterization of the Borikiri coastal aquifer system. The subsurface is dominated by sandy formations with minor clay interbeds typical of the Niger Delta coastal plain sands. Moderate to high resistivity values within the principal water-bearing units indicate freshwater-saturated sands with favourable hydraulic properties, while computed transverse

resistance values suggest moderate to high transmissivity suitable for groundwater abstraction.

Spatial variation in longitudinal conductance reveals uneven protective capacity, with some locations exhibiting limited natural confinement due to thin or discontinuous clay cover. Although the resistivity structure does not indicate extensive saline intrusion within the investigated depth range, the proximity to the estuarine environment highlights potential vulnerability under sustained abstraction.

The results demonstrate that resistivity sounding integrated with Dar-Zarrouk analysis offers a practical and cost-effective framework for rapid aquifer assessment in data-scarce coastal terrains. Complementary borehole and hydrochemical data are recommended to further constrain hydraulic estimates and long-term groundwater sustainability.

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