E-ISSN: 1115 – 8492 P-ISSN: 3027 – 0693
MPRI-JNSAR | INTERNATIONAL JOURNAL OF NATURE AND SCIENCE ADVANCE RES.
VOL. 12 NO. 9 APRIL-2026

ANALYSIS OF HYDRAULIC CHARACTERIZATION AND GROUNDWATER QUALITY ASSESSMENT OF UPPER AND DEEP AQUIFER PROSPECTS IN OGONILAND, SOUTHERN NIGERIA

R. E. AKPODEE[1]; D. L. IKUE[2]

[1]Department of Mathematics, Faculty of Science, Rivers State University, Port Harcourt, Nigeria.
[2]Institute of Geosciences and Environmental Management, Rivers State University, Port Harcourt, Nigeria

Corresponding Authors:
akpodeerichard@yahoo.com

DOI: https://doi.org/10.70382/mejnsar.v12i9.086

Abstract

Groundwater is the primary source of potable water in Ogoniland, Southern Nigeria, where increasing anthropogenic pressures particularly oil exploration activities pose significant risks to aquifer systems. Understanding the hydraulic characteristics and groundwater quality variation across aquifer depths is therefore essential for sustainable water resource management in the Niger Delta. This study investigates the hydraulic properties and hydrochemical characteristics of the upper and deep aquifer systems in Ogoniland, with emphasis on vertical variability, aquifer connectivity, and water quality status. The study employed an integrated hydrogeological approach involving borehole lithologic data, downhole logging, pumping test analysis, and groundwater sampling across selected communities in four Local Government Areas. Hydraulic parameters such as hydraulic conductivity, transmissivity, storativity, static water level, and hydraulic head were determined. Physicochemical, hydrochemical, heavy metal, hydrocarbon, and microbiological analyses were conducted using standard laboratory procedures, while hydrochemical facies were evaluated using Piper diagram interpretation. Statistical analyses were performed using

Keywords: Aquifer Characterization, Hydraulic Conductivity, Groundwater Quality, Hydro chemical Facies, Niger Delta, Saline Intrusion, Ogoniland

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descriptive and inferential methods to assess spatial variations. Results indicate that the upper aquifer thickness ranges from 15 to 80 m, while the deep aquifer varies from 20 to 85 m, confirming significant spatial heterogeneity. Hydraulic conductivity in the upper aquifer ranges from 15.31 to 264 m/day, with transmissivity between 371 and 20,880 m^2/day, while the deep aquifer shows conductivity values of 7.92 to 264 m/day and transmissivity between 158.39 and 7,776 m^2/day. Storativity values (10^{-4}–10^{-7}) indicate semi-confined conditions in both aquifers. Groundwater flow is predominantly from northern elevated zones (up to 41.27 masl) toward southern low-lying areas (as low as 26.21 masl). Hydrochemical analysis reveals low total dissolved solids (3–58 mg/L) and electrical conductivity (7–116 µS/cm), indicating fresh groundwater, with pH ranging from 5.66 to 7.05. The dominant hydrochemical facies is calcium–chloride (Ca–Cl), suggesting the influence of marine processes, ion exchange, and water–rock interactions. Most heavy metals and hydrocarbons are below permissible limits, although localized iron concentrations (up to 1.03 mg/L) and minor PAH presence indicate site-specific contamination. Microbiological analysis shows minimal contamination, with low total coliform counts in some locations. The study concludes that groundwater in Ogoniland is generally of good quality and suitable for domestic use; however, the semi-confined nature of the aquifer system and the presence of a discontinuous clay layer increase vulnerability to contamination and saline intrusion. Hydraulic connectivity between aquifers further enhances the risk of vertical pollutant migration. It is recommended that continuous groundwater monitoring be implemented, particularly in oil-producing and coastal areas. Improved borehole design and protection of recharge zones are necessary to reduce contamination risks. Additionally, stricter environmental regulations and further studies incorporating advanced hydrogeochemical and isotopic techniques are essential for sustainable groundwater management in the region.

Introduction

Access to safe and dependable drinking water is crucial for human health, sustainable development, and overall well-being, constituting a fundamental goal of water supply, sanitation, and hygiene (WASH) initiatives (Hutton & Chase, 2016). Groundwater is a very important natural resource in this case because it is a reliable source of fresh water in many rural and urban areas where surface water is scarce or polluted. In developing areas like the Niger Delta, where groundwater meets the needs of homes, farms, and businesses, it is especially important. Groundwater makes up about

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30% of the world's fresh water and is used to get a lot of the water that people use (Taylor et al., 2012).

The Niger Delta, which includes Ogoniland in Rivers State, is a busy area because oil and gas exploration is going on all over the place. These activities help the economy grow, but they also put a lot of stress on water resources, making it more likely that hydrocarbons, gas flaring, and industrial effluents will pollute them (UNEP, 2011; Nnabuenyi, 2012). Human activities like throwing away trash in the wrong way, runoff from farms, and cities growing bigger make groundwater even more vulnerable (Akporido, 2008; Mitra & Roy, 2011). Organic pollutants, particularly BTEX compounds (benzene, toluene, ethylbenzene, and xylene), are concerning due to their high solubility, mobility, and potential health effects, including carcinogenicity, liver and kidney dysfunction, and neurological disorders (Li & Zhou, 2011; Uzoekwe & Oghosanine, 2011).

The Benin Formation in Ogoniland has multi-layered aquifer systems that store groundwater. These systems are made up of layers of coarse sands, fine to silty sands, and clay layers that are mixed in with each other (Etu-Efeotor & Akpokodje, 1990; Akpokodje et al., 1996). These hydrostratigraphic units create both shallow (upper) and deeper aquifers. A clay layer that doesn't connect them completely acts as a semi-confining horizon. This layer's discontinuity makes it possible for limited vertical recharge and the movement of contaminants from the surface or shallow aquifers into deeper systems (UNEP, 2020; Olobaniyi & Nwankwoala, 2022). Consequently, comprehending the hydraulic properties of these aquifers is essential for assessing groundwater availability, susceptibility, and long-term viability in Ogoniland.

Groundwater is very important in Ogoniland, but most of the research that has been done so far has been on the presence of contaminants, especially hydrocarbon pollution. These studies have not included detailed hydraulic characterization of both shallow and deep aquifers (Etu-Efeotor & Odigi, 1983; Edet et al., 2014). To manage groundwater resources well, you need to know a lot about the aquifer's thickness, depth, hydraulic conductivity, transmissivity, and storage properties. This includes designing boreholes, placing wells, and protecting recharge zones.

This study focuses on the hydraulic characterization of upper and deep aquifer prospects in Ogoniland, with the following objectives: (1) delineate the upper and deep aquifer intervals using borehole lithologic and downhole data, (2) evaluate the hydraulic properties and spatial variability of the aquifers, and (3) assess groundwater quality across different depths to identify potential contamination pathways. This study seeks to deliver a thorough comprehension of the aquifer system through the integration of hydrogeological and water quality analyses, thereby guiding sustainable groundwater development, protection measures, and public health initiatives in this oil-affected area.

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Study Area

Ogoniland is located in the southern Nigerian region of the Eastern Niger Delta, within Rivers State, east of Port Harcourt and near the Gulf of Guinea coast. The region encompasses an area of approximately 1,050 km² (404 mi²), making it the third-largest mangrove ecosystem in the world, and is home to an estimated population of 832,000 people according to the 2006 National Census. The Ogoni region lies between latitudes 5°11′510″–5°24′485″ N and longitudes 6°30′830″–6°32′831″ E on the Greenwich meridian. The local population is predominantly engaged in farming and fishing, with livelihoods closely tied to the rivers, estuaries, and wetlands of the Niger Delta.

Administratively, Ogoniland is divided into four Local Government Areas (LGAs): Khana, Gokana, Tai, and Eleme. Each LGA comprises several communities that were included in this study to capture spatial variability in aquifer properties and groundwater quality. Two representative communities were selected in each LGA for detailed hydrogeological investigations:

- Khana LGA: Bomu and Taabaa
- Gokana LGA: K-Dere and Bodo
- Tai LGA: Beeri and Uegwere
- Eleme LGA: Ebubu and Onne

The study focused on the hydrogeology and groundwater characteristics across these communities, representing a cross-section of both inland and coastal settings, as well as areas with varying exposure to anthropogenic activities such as oil exploration, gas flaring, and urbanization.

Field investigations involved the drilling of eight boreholes in each LGA, totaling 32 boreholes across the four LGAs. Borehole depths ranged from 20 to 150 meters, targeting both the shallow (upper) and deep aquifer systems. Borehole logs and lithological data were used to delineate aquifer intervals and screen different sections within each borehole, enabling hydraulic characterization of the aquifers. The multi-depth boreholes provided insights into aquifer thickness, lithology, hydraulic properties, and connectivity, while water samples collected at various depths facilitated assessment of groundwater quality variations across both aquifers and communities.

The selection of communities and borehole locations was based on criteria including proximity to major rivers, population density, accessibility, and representativeness of the different hydrogeological units within Ogoniland. This approach ensured that the study captured both spatial and vertical variations in aquifer characteristics and groundwater quality across the region.

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Figure 2.1: Map of Rivers State Showing Study Area



Figure 2.2: Map of Study Area

Study Design

This study adopted a descriptive and exploratory research design with both field-based hydrogeological investigation and laboratory-based groundwater quality analysis**.** The primary objective was to characterize the upper (shallow) and deep aquifer systems in Ogoniland and to evaluate variations in groundwater quality across depth and space, particularly in relation to lithological and hydraulic properties.

Research Approach

A mixed-method approach was employed:

- Quantitative field measurements: to determine hydraulic properties such as static water level, transmissivity, hydraulic conductivity, and aquifer thickness from borehole data.
- Qualitative and chemical analysis: to determine the hydrochemical, physicochemical, and microbiological characteristics of groundwater from both shallow and deep aquifers.

This dual approach allowed for the correlation of aquifer characteristics with observed groundwater quality patterns.

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Borehole Drilling and Aquifer Screening

A total of 32 boreholes were drilled across the four LGAs of Ogoniland, with eight boreholes per LGA, distributed across two representative communities in each LGA:

- Khana LGA: Bomu and Taabaa
- Gokana LGA: K-Dere and Bodo
- Tai LGA: Beeri and Uegwere
- Eleme LGA: Ebubu and Onne

Boreholes were drilled to depths ranging from 20 to 150 meters, targeting both shallow and deep aquifer systems. Downhole geophysical logs and lithologic data were used to delineate aquifer intervals and determine the top and bottom of the screened sections for each aquifer. This approach enabled precise hydraulic characterization of both aquifer units.

Hydraulic Characterization

Hydraulic parameters measured or estimated included:

- Static water level (SWL)
- Hydraulic head
- Transmissivity (T)
- Hydraulic conductivity (K)
- Storativity (S)

Standard field techniques, including slug tests, pumping tests, and flow measurements, were used to quantify these properties. The data provided insight into aquifer heterogeneity, recharge potential, and yield capacity of both shallow and deep aquifers.

Groundwater Sampling and Quality Assessment

Water samples were collected at different depth intervals in each borehole to assess vertical variation in groundwater quality. Laboratory analyses included:

- Physicochemical parameters: pH, temperature, electrical conductivity, total dissolved solids (TDS), and salinity.
- Major ions: Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Chloride (Cl^{-}), Sulfate (SO_4^{2-}), and Bicarbonate (HCO_3^{-}).
- Trace metals: Iron (Fe), Zinc (Zn), and other metals relevant to health risk assessment.
- Microbiological indicators: Total coliforms, fecal coliforms, and E. coli.

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Data were used to generate Piper diagrams, water quality indices (WQI), and hydrochemical facies classification to evaluate groundwater suitability for domestic, agricultural, and industrial use.

Method of Solution for Data Analysis

Dispersion Statistics and Mathematical Formulation for PH Concentration and Ions Concentration Relative Abundance Projection in Ground Water

In this study, the spatial and vertical distribution of groundwater constituents, including pH, major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), and anions (Cl^{-}, SO_4^{2-}, HCO_3^{-}), was analyzed using dispersion statistics and relative abundance formulations. Following the approach of Abel and Tosin (2019), regions of elevated contaminant concentration in groundwater were conceptualized as pollutant plumes. These plumes represent localized zones where hydrochemical constituents or pollutants are concentrated within an aquifer and can be visualized as three-dimensional "clouds" moving through groundwater systems.

Within these plumes, constituent concentrations are not uniform. The highest concentrations are typically observed along a central axis, referred to as the plume centerline, while concentrations gradually decrease laterally and vertically away from this axis. This pattern is commonly described by a Gaussian or bell-shaped distribution, which provides a convenient model for statistical analysis and projection of constituent dispersion across depth intervals.

Plume Center of Mass and Depth-Weighted Concentration

To quantitatively assess the vertical distribution of groundwater parameters, the plume centerline depth (z_cl) was calculated. The centerline represents the weighted average depth at which a constituent, such as pH or a specific ion, is most concentrated. For a set of equally spaced depth intervals (z_k) through a borehole or screened aquifer interval, the centerline depth is defined as the concentration-weighted mean:

Plume Center of Mass (Plume Center line depth)

With regard to depth z_cl, the plume centerline is the position of the center of mass of pollutants. It is the average depth of the contaminants, to put it another way. The center of mass is a weighted average determined by measuring the concentration c_k of pollutants at a range of equally spaced depths z_k through the source pollutant plume (Okaba and Akpodee, 2024):

$$z_{cl} = \overline{z} = \frac{\sum_{k=1}^{K} c_k . z_k}{\sum_{i=1}^{K} c_k} \qquad 2.1$$

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where the overbar indicates a mean, K is the total number of depth partitions, and k is the depth index. For passive tracers that have a sluggish velocity of departure from the source pollutant, the plume centerline is situated at the same depth as the top of the source pollutant.

Plume Standard Deviation – Sigma

Determining the boundaries of time-averaged pollutant plumes is inherently difficult. Because the concentration profile of a plume gradually approaches zero away from the central axis, the edges are not sharply defined and cannot reliably indicate the full depth or lateral extent of plume dispersion. Instead, the vertical spread of the plume is quantified using the standard deviation (δ_z) of pollutant positions. The standard deviation, defined as the square root of the variance (δ_z²), provides a statistical measure of plume thickness. To accurately represent the distribution, δ_z is calculated by weighting the deviations of each vertical position from the plume centerline by the local pollutant concentration (Okaba and Akpodee, 2024):

$$\delta_z = \left[\frac{\sum_{k=1}^{K} c_k.(z_k-\overline{z})^2}{\sum_{k=1}^{K} c_k}\right]^{1/2} \quad 2.2$$

Where $\overline{z} = z_{cl}$ is the average height as determined by the equation for the center of mass.

Gaussian Plume Curve Model

The diffusion problem can be solved using the Gaussian concentration distribution (Okaba and Akpodee, 2024).

The budget equation for a conservative, passive tracer states that if more tracer flux F_c enters a volume than exits, with time t, a volume's concentration c will increase This can be written as follows:

$$\frac{dc}{dt} = -\frac{\partial F_c}{\partial z} \quad 2.3$$

If the turbulence has only small eddies, the turbulent flux of tracer flows down the mean tracer gradient is computed as follows:

$$F_c = -K\frac{\partial c}{\partial z} \quad 2.4$$

where F_c is expressed in kinematic units (concentration times velocity), and similar to a molecular diffusivity, the eddy diffusivity is denoted by K. The 1-D diffusion equation is calculated as follows when equation 3.13 is substituted into equation 3.12:

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$$\frac{dc}{dt} = K.\frac{\partial^2 c}{\partial z^2} \quad 2.5$$

This parabolic differential equation can be solved using either boundary conditions (BC) or beginning conditions (IC). The dispersion is up and down the pipe is one-dimensional, and we define the vertical coordinate system such that z=0 at the starting puff height and ∑z=0. Imagine that a vertical pipe filled with clean air at time t=0 emits a smoke puff with mass Q grams of tracer in the center. With the initial condition IC: $c = 0\ at\ t = 0$ everywhere except at $z = 0$. And with boundary condition I BC1: $\int cdz = Q$ at all t, where limit of integration ranges from $-\infty\ to\ \infty$ and boundary condition II BC2: $c\ approaches\ 0\ as\ z\ approaches\ \pm\infty\ at\ all\ t$. The analytical solution becomes:

$$C = \frac{Q}{(4\pi Kt)^{1/2}}.\exp\left(\frac{-z^2}{4Kt}\right) \quad 2.6$$

Where $\delta_z = \sqrt{2Kt}$ 2.7

It claims that tracer spread increases with the square root of time and that a higher eddy-diffusivity leads to a faster spread rate. Consequently, the gaussian plume's necessary solution is expressed as follows:

$$C(z) = \frac{Q_1}{\delta_z.\sqrt{2\pi}}.\exp\left(-0.5\left[\frac{z}{\delta_z}\right]^2\right) \quad 2.8$$

The Gaussian or "normal" curve is bell shaped, and is given in one-dimension (1-D) for $\overline{z} \neq 0$ as:

$$C(z) = \frac{Q_1}{\delta_z.\sqrt{2\pi}}.\exp\left(-0.5\left[\frac{z-\overline{z}}{\delta_z}\right]^2\right) \quad 2.9$$

where c(z) is the one-dimensional concentration (g/ m) at any depth z, and Q_1 (g) is the total amount of pollution released, calculated as:

$$Q_1 = \Delta z.\sum_{i=1}^{K} c_k \quad 2.10$$

where Δz is the step size, or depth gap, between adjacent measurements.

Existence of solutions for initial value problems

This subsection discusses the qualitative analysis of ordinary differential equation initial-value problems. The following definitions can be provided with reference to the class of mathematical formulations mentioned above:

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Well-Posedness

In groundwater modeling, a problem is considered well-defined when the governing equations of flow and transport are accompanied by the appropriate initial and boundary conditions. It is well-posed if the solution exists, is unique, and depends continuously on the initial and boundary data. For aquifer studies, the main objective of a model is to predict groundwater behavior—such as hydraulic heads, flow velocities, or contaminant concentrations—over a specified time period, starting from observed conditions at an initial time t_0

The resulting initial-value problem is then solved to generate predictions of aquifer response.

For a groundwater model to be considered well-posed, it must satisfy the following criteria:

i) Existence – A solution should be obtainable at least for the time frame of interest.

ii) Uniqueness – The solution must be distinct and not ambiguous.

iii) Stability – Small uncertainties or errors in initial or boundary conditions should produce only minor variations in the solution, reflecting continuous dependence on input data and aquifer parameters.

By ensuring that these conditions are met, the model can reliably represent the hydraulic behavior of both the upper and deep aquifers in Ogoniland and provide meaningful predictions for groundwater management and contamination assessment.

Numerical Iterations Mathematical Preliminaries

According to Akpodee (2019), when analytical solutions for initial value problems (IVPs) are not feasible, numerical methods become necessary. Among the various techniques for solving IVPs, this study focuses on the widely applied fourth-order Runge-Kutta (R-K) method. The following section outlines the theoretical basis and mathematical formulation of this method. The fourth-order Runge-Kutta approach is recognized for its accuracy and flexibility, as it approximates the solution of the function f(x,y) using a Taylor series expansion.

$$\frac{dy}{dx} = f(x, y) \qquad 2.11$$

Subject to the initial condition $y\ (x_o) = y_o$

Despite the possibility of variation at each step, the increment h in x is frequently kept constant so that, after n steps, we obtain

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$$x_n = x_o + nh \qquad 2.12$$

The approximation is determined using the Runge-Kutta algorithm y_{n+1} to $y(x_{n+1})$ is

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \qquad 2.13$$

Where,

$$k_1 = hf(x_{n,}y_{n,})$$
$$k_2 = hf(x_n + \frac{1}{2}h,\ y_n + \frac{1}{2}k_1)$$
$$k_3 = hf(x_n + \frac{1}{2}h,\ y_n + \frac{1}{2}k_2)$$
$$k_4 = hf(x_{n+1,}y_n + k_3)$$

The local mistake in the calculation of y_{n+1} from y_n is $0(h^5)$

The aforementioned technique can be expanded to solve a differential equation system like

$$\frac{dy}{dx} = f(x, y, z) \qquad 2.14$$

$$\frac{dz}{dx} = g(x, y, z) \qquad 2.15$$

Subject to the initial condition $y\ (x_o) = y_o$ and $z\ (x_o) = z_o$ 2.16

This research considers such equations and consists of a system of two first order nonlinear differential equations.

The Runge-Kutta Algorithm for the system has the following form at the nth integration step using a step of length h:

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \qquad 2.17$$

$$z_{n+1} = z_n + \frac{1}{6}(K_1 + 2K_2 + 2K_3 + K_4) \qquad 2.18$$

Where,

$$k_1 = hf(x_{n,}y_{n,}z_n)$$
$$k_2 = hf(x_n + \frac{1}{2}h\ ,\ y_n + \frac{1}{2}k_1,\ z_n + \frac{1}{2}K_1)$$
$$k_3 = hf(x_n + \frac{1}{2}h\ ,\ y_n + \frac{1}{2}k_{2,}z_n + \frac{1}{2}K_2)$$
$$k_4 = hf(x_n + h\ ,\ y_n + k_3,\ \ z_n + K_3)$$

and

$$K_1 = hg(x_{n,}y_{n,}z_n)$$

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$$K_2 = hg(x_n + \frac{1}{2}h\ ,\ y_n + \frac{1}{2}k_{1,}z_n + \frac{1}{2}K_1)$$
$$K_3 = hg(x_n + \frac{1}{2}h\ \ ,\ y_n + \frac{1}{2}k_2,\ z_n + \frac{1}{2}K_2)$$
$$K_4 = hg(x_n + h\ ,\ y_n + k_3z_n + K_3)$$

Similar to the Runge-Kutta approach, the local inaccuracy in figuring out y_{n+1} from y_n and z_{n+1} from z_n is $0(h^5)$ 3.28

According to good numerical analysis practice, we must use a different approach to investigate the qualitative elements of these interactions in situations where an analytical solution for impact and sensitivity analysis of water quality cannot be admitted by a complicated dynamical system. The MATLAB ODE45 numerical scheme is used to computationally solve this difficult environmental problem.

The following is the study's submission and justification for using the numerical simulation approach (iterations) for the mathematical model formulation of the water quality projection:

i. Due to its many environmental complications, the closed-form solution (exact solution by direct integration) may be extremely complex and challenging to assess analytically.
ii. There is no alternative option, which is to state that there isn't a closed-form solution in such a scenario.
iii. The computing technique needed a large number of steps (iterations) with a selected small step size in order to acquire a considerable amount of roundoff error.
iv. Several precision calculations on our forecasts and predictions will be improved by this method.
v. Water quality variables' relative abundance and pollutant stock can be accurately assessed due to their engagement in climate change and environmental protection agencies' decision-making and policy-making processes.

Statistical Analysis

For thorough data analysis, the IBM Statistical Package for Social Sciences (SPSS version 25.0) and statistical techniques included in Microsoft Excel will be used. The sample locations will be described in terms of their physicochemical attributes using descriptive statistics, such as measurements of dispersion (standard deviation, variance) and central tendency (mean, median, mode). Tables and charts, such as pie charts, bar graphs, and frequency tables, will be used to display the data. To assess the differences between several sampling points, a one-way analysis of variance (ANOVA) will be carried out. The purpose of this test is to ascertain whether the differences between the sampling points

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were statistically significant. When significant differences are found ($P < 0.05$), Duncan's Multiple Range (DMR) Test will be used for a post-hoc analysis. The particular sampling points that were substantially different from one another will be identified with the use of this post-hoc test.

Results

Table 3.1: Hydraulic characterization of upper aquifer and deep aquifer prospects in the study area

Borehole Location	Borehole ID	Aquifer Type	Easting (mN)	Northing (mN)	Elevation (masl)	Static Water level (mbgl)	Hydraulic Head (m)	Hydraulic conductivity (m/day)	Transmissivity (sq.m/day)	Storativity
Bomu		Upper Aquifer	511510	312276	29.79	6.44	23.35	261.00	20880	1.00E-04
Borobara			523668	304933	38.06	12.88	25.18	66.60	1998	1.00E-07
Deken			520945	311457	27.98	-	-	20.34	1220.4	3.34E-05
Eteo			524803	298856.6	31.72	8.90	22.82	18.55	371	1.00E-04
K-Dere			515112	307995.2	30.47	7.60	22.87	15.31	995.28	1.00E-07
Onne			522899	295228.9	28.41	7.67	20.74	264.00	11880	1.00E-07
Taabaa			523571	325380	41.27	12.21	29.06	191.00	9550	5.01E-05
								119.54	6699.24	4.05E-05
Beeri		Deep Aquifer	518771	325333	38.2	11.65	26.55	264.00	6336	3.34E-05
Bodo			512895	308673.5	31.6	9.57	22.03	7.92	158.39	1.00E-07
Barayira			524467	300872	27.26	4.14	23.12	103.68	7776	1.00E-04
Ebubu			528744	294765.3	35.61	6.51	29.10	103.68	7776	1.00E-04
Kporghor			520680	303534.9	26.21	8.57	17.64	63.45	3807	3.34E-05
Kpean			510638	328346.9	31.2	5.82	25.38	86.40	5184	3.34E-05
Uegwere			513285	317967	31.83	8.13	23.70	39.10	2346	1.00E-07
Korokoro			523750	312544.6	32.1	4.79	27.31	17.86	803.52	1.00E-07
Ogale			530297	293160.8	29.86	-	-	108.55	4342	5.01E-05
								88.29	4280.99	3.90E-05

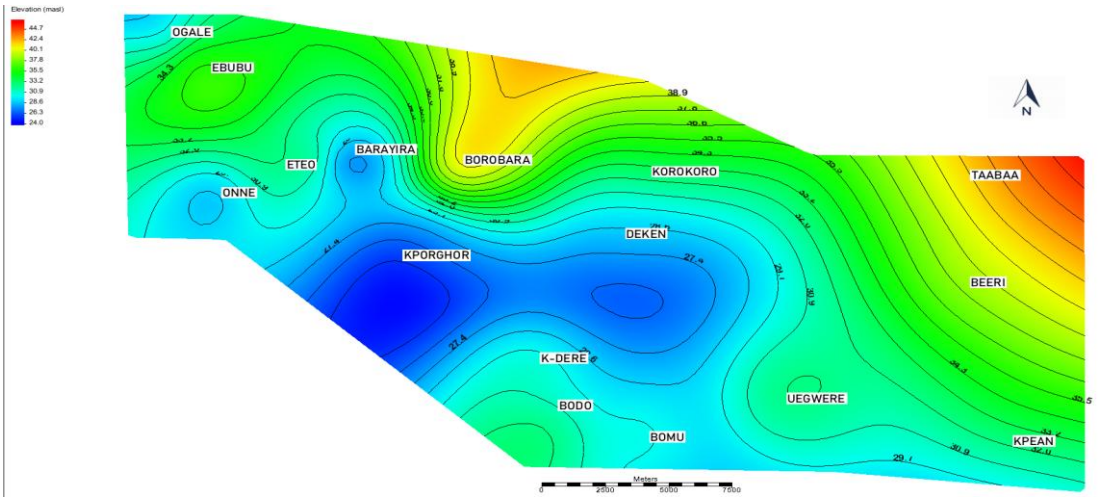


Figure 3.1: Map showing Elevation profile across the study area

The study area's elevation data show a mild north-south gradient, with lower elevations toward the south, especially around Kporghor (26.21 masl), Barayira (27.26 masl), and Deken (27.98 masl), which are closer to the Bonny River and its distributary channels, and

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higher elevations in the northern communities like Taabaa (41.27 masl), Beeri (38.20 masl), and Borobara (38.06 masl). In accordance with the Niger Delta's regional drainage and depositional processes, this topographic layout establishes the natural direction of groundwater flow from the higher northern zones toward the lower southern floodplains.

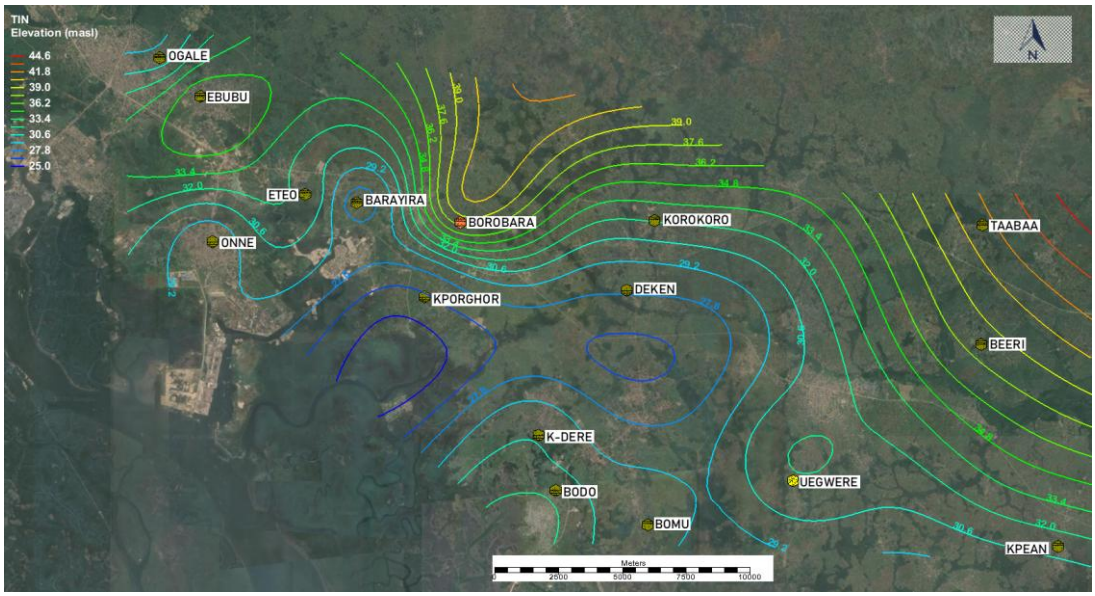


Figure 3.2: Map showing Elevation profile across the study area overlain on google earth

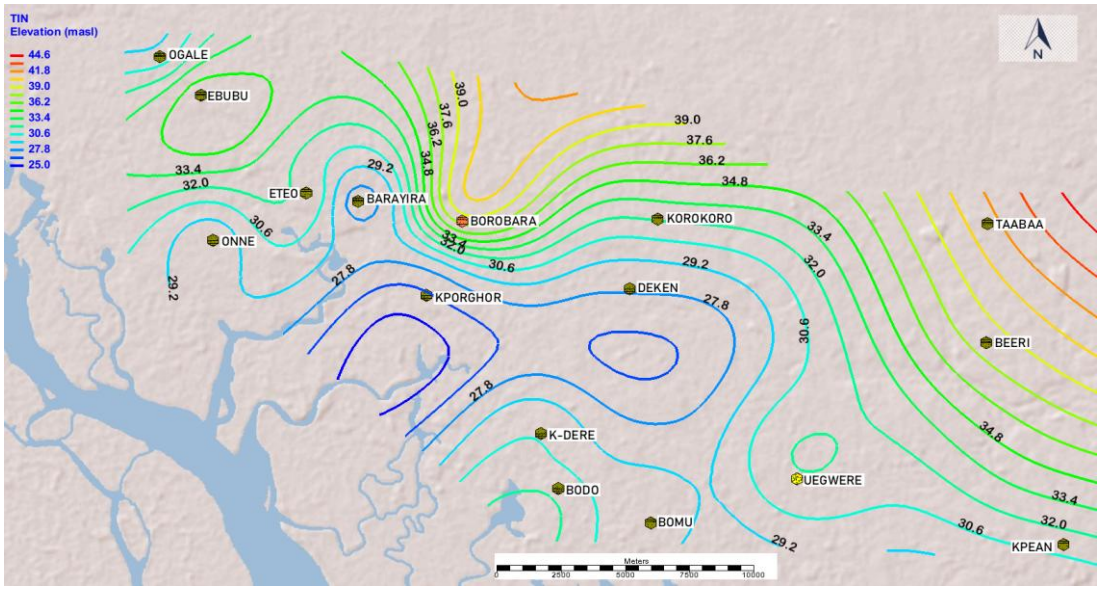


Figure 3.3: Map showing Elevation profile across the study area relative to surrounding Riverine systems and creeks

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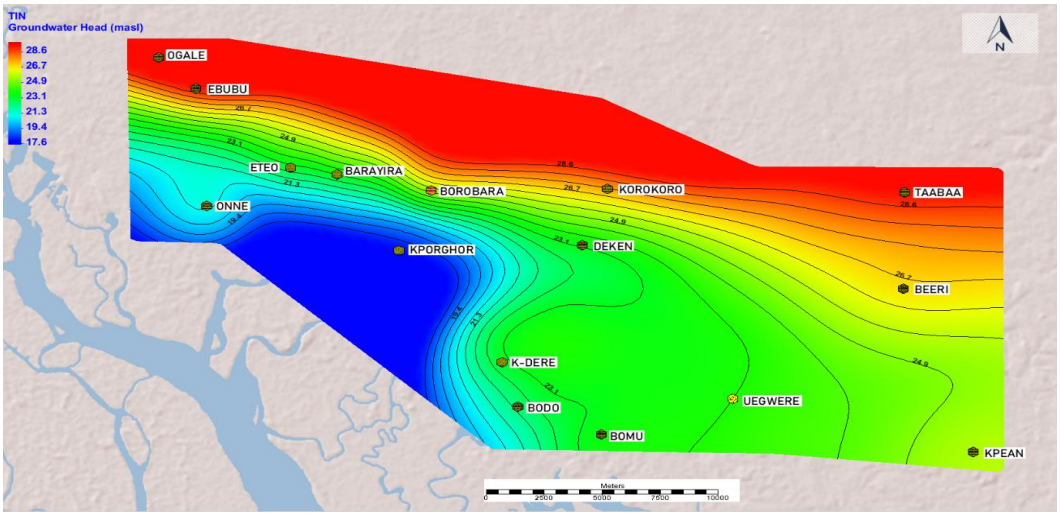


Figure 3.4: Groundwater hydraulic heads distribution across the study area

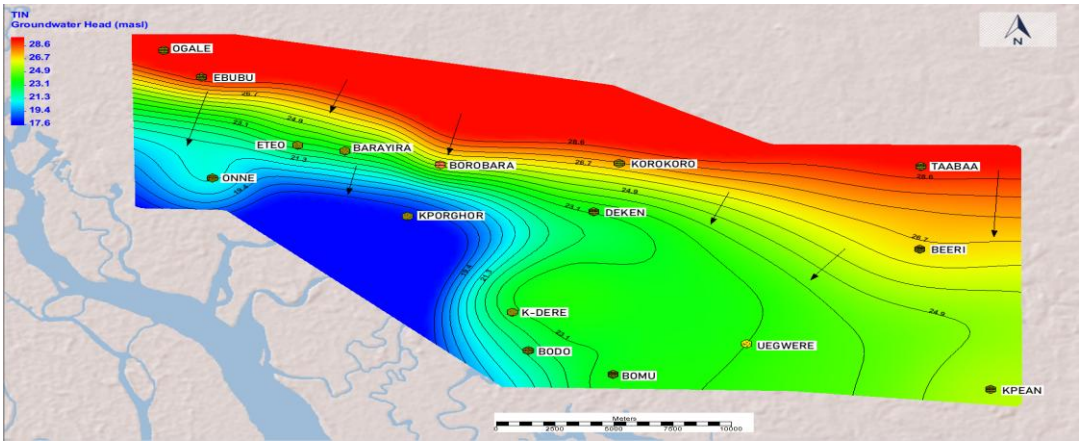


Figure 3.5: Groundwater flow direction across the study area

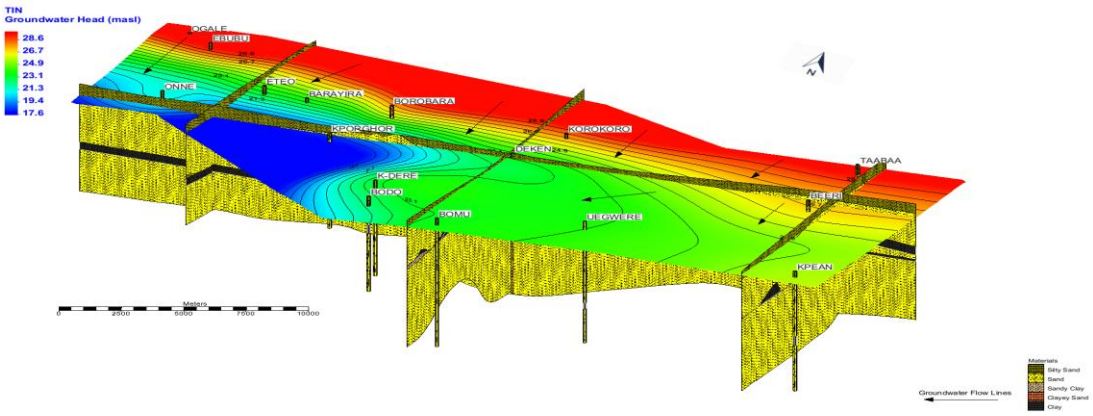


Figure 3.6: Groundwater flow model overlain on fence diagram developed across the study area

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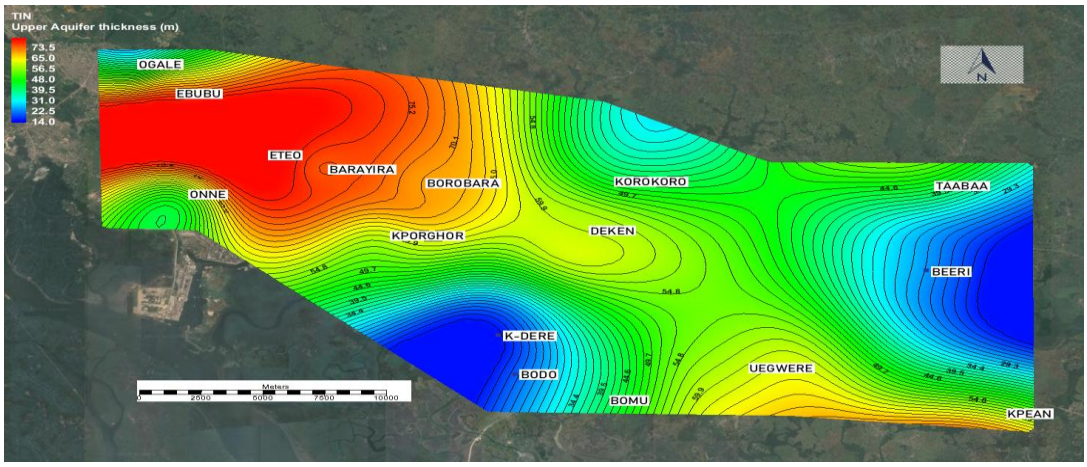


Figure 3.7: Map showing thickness across the upper aquifer

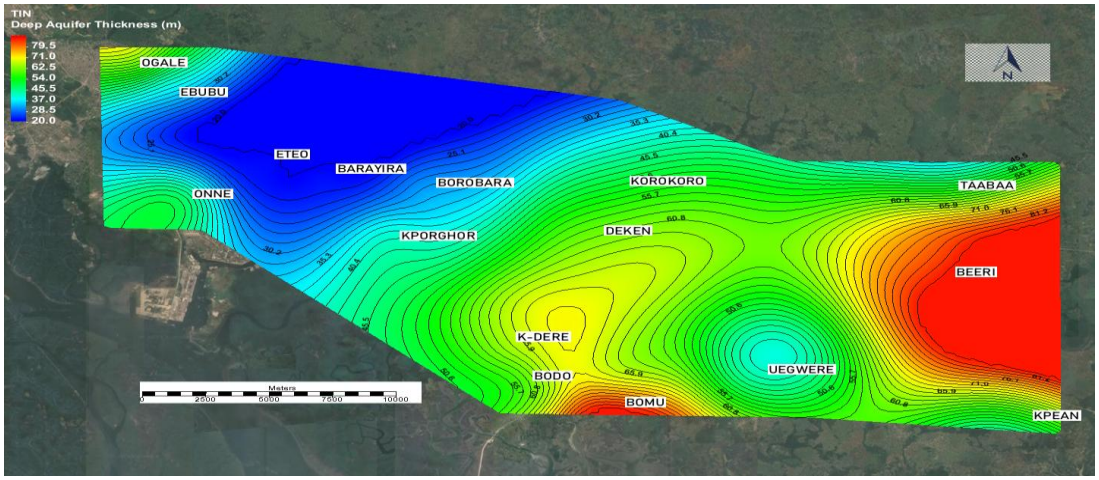


Figure 3.8: Map showing thickness across the deep aquifer

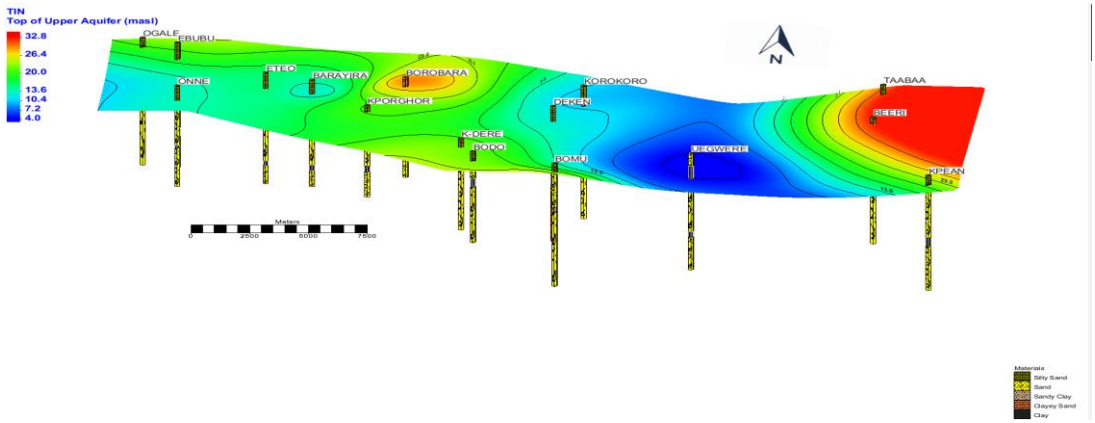


Figure 3.9: Model showing boreholes relative to top of upper aquifer across the study area

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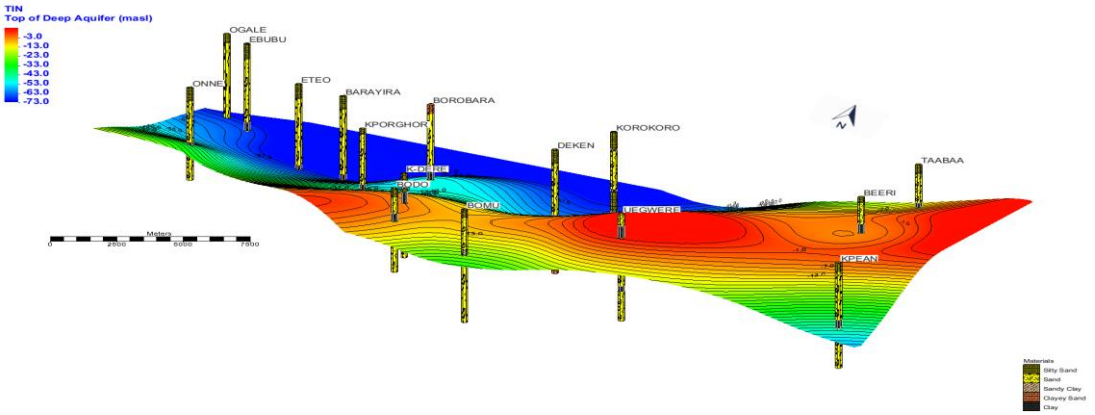


Figure 3.10: Model showing boreholes logs relative to top of deep aquifer across the study area

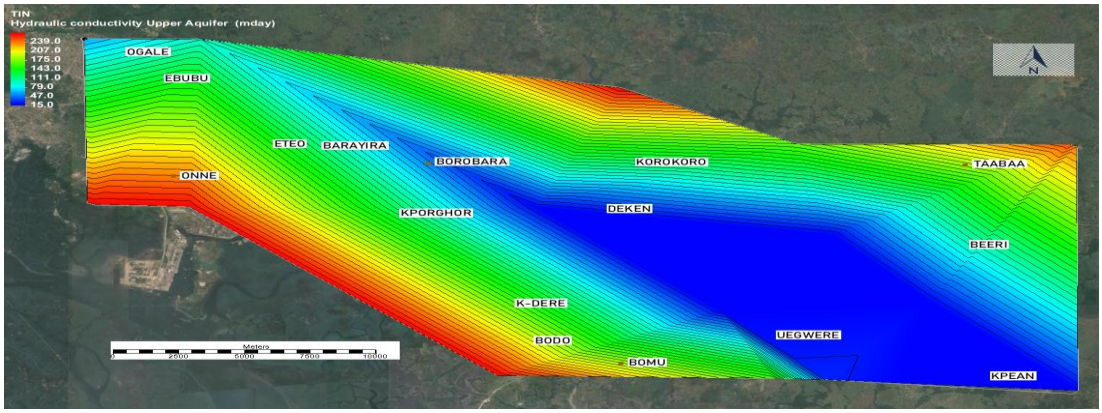


Figure 3.11: Model showing hydraulic conductivity distribution for the upper aquifer across the study area

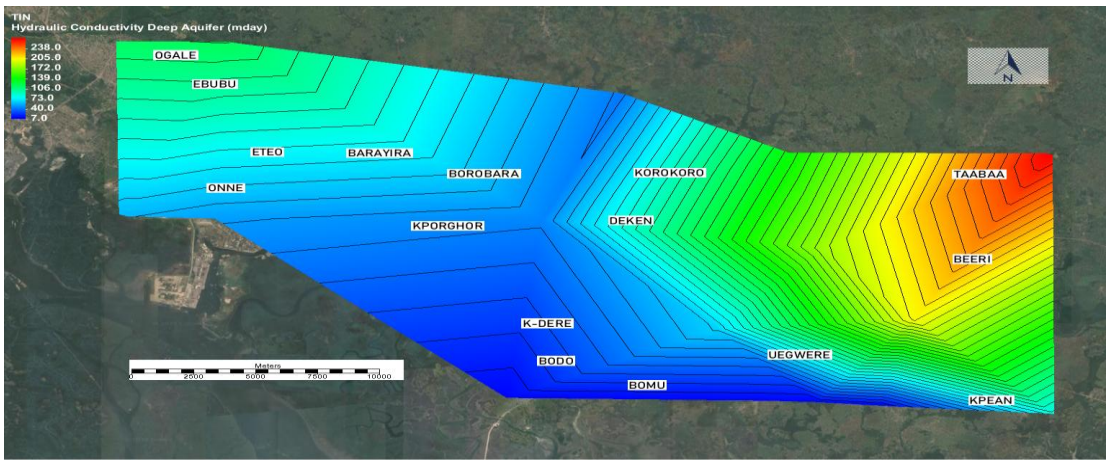


Figure 3.12: Model showing hydraulic conductivity distribution for the deep aquifer across the study area

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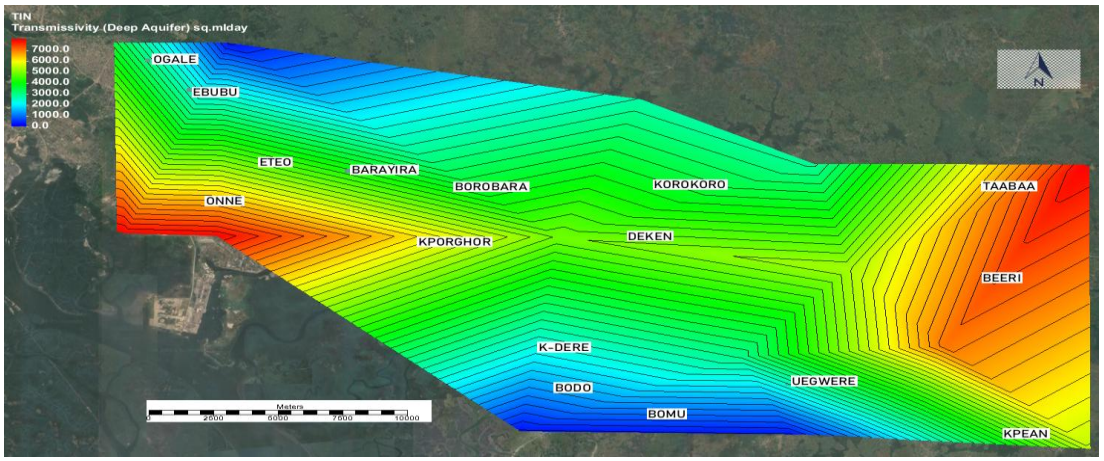


Figure 3.13: Model showing transmissive distribution for the upper aquifer across the study area

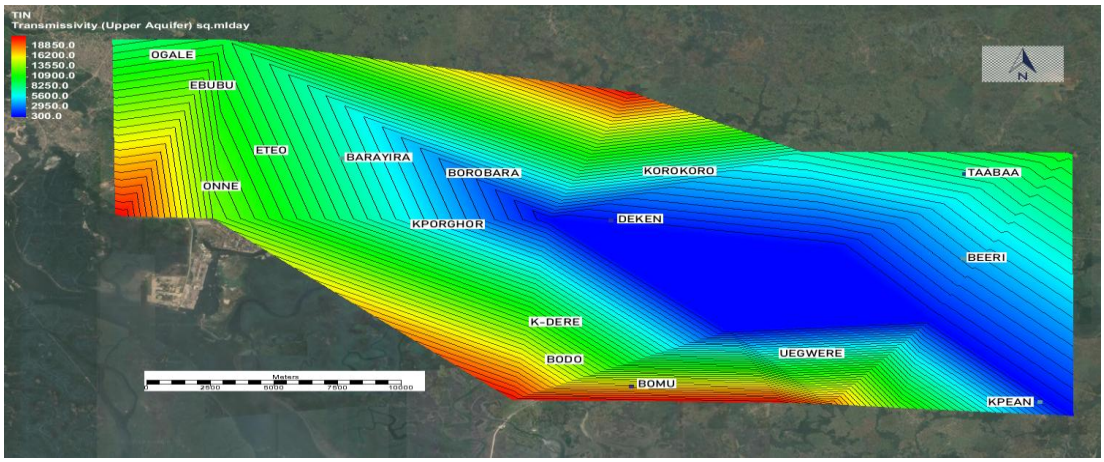


Figure 3.14: Model showing transmissivity distribution for the deep aquifer across the study area

Table 4.2: Statistical summary of groundwater parameters for the upper aquifer compared with regulatory standards

Parameter	Unit	Min	Max	Average	S.D	WHO (2006)
Physical						
Temperature, OC	OC	23.00	29.10	26.67	2.12	-
Colour	TCN	0.50	1.00	0.93	0.19	-
Odour	TON	1.00	1.00	1.00	0.00	-
Taste		Un-obj	Un-obj	Un-obj	Un-obj	-
Turbidity	NTU	<0.01	0.30	0.15	0.21	5
Ph		5.66	7.05	6.21	0.42	6.5-8.5

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Parameter	Unit	Min	Max	Average	S.D	WHO (2006)
Electrical Conductivity	uS/cm	7.00	116.00	34.90	36.33	1000
Total Dissolved Solids	mg/L	3.00	58.00	17.13	18.31	500
Total Hardness	mgCaCO3/L	<0.01	10.00	6.86	3.02	300
Total Suspended Solids	mg/L	<0.001	1.00	1.00		-
Chemical Oxygen Demand	mg/L	<0.01	3.80	3.80		-
Total Alkalinity	mgCaCO3/L	2.00	22.00	8.33	7.09	150
Total Acidity	mgCaCO3/L	4.00	34.00	14.00	12.57	-
Cations and Anions						-
Calcium	mg/L	0.01	3.68	1.42	1.51	75
Sodium	mg/L	0.01	0.11	0.06	0.05	200
Potassium	mg/L	<0.001	0.03	0.03		50
Magnesium	mg/L	0.03	0.37	0.14	0.14	-
Nitrate	mg/L	<0.001	0.02	0.01	0.01	50
Nitrite	mg/L	<0.001	<0.001	<0.001	<0.001	3
Sulphide	mg/L	<0.1	<0.1	<0.1	<0.1	250
Chloride	mg/L	<0.1	5.90	2.42	2.36	250
Free Chlorine	mg/L	<0.01	<0.01	<0.01	<0.01	-
Heavy Metals						
Arsenic	mg/L	<0.001	<0.001	<0.001	<0.001	0.01
Cadmium	mg/L	<0.001	<0.001	<0.001	<0.001	-
Chromium	mg/L	<0.001	<0.001	<0.001	<0.001	0.05
Copper	mg/L	<0.001	<0.001	<0.001	<0.001	1
Iron	mg/L	<0.001	1.03	0.38	0.56	0.3
Lead	mg/L	<0.001	<0.001	<0.001	<0.001	0.01
Zinc	mg/L	<0.001	<0.001	<0.001	<0.001	5
Aluminum	mg/L	<0.001	<0.001	<0.001	<0.001	0.2
Nickel	mg/L	<0.001	<0.001	<0.001	<0.001	-
Manganese	mg/L	<0.001	<0.001	<0.001	<0.001	0.2
Mercury	mg/L	<0.001	<0.001	<0.001	<0.001	-
Hydrocarbons						
TPH	mg/L	<0.001	<0.001	<0.001	<0.001	50
PAH	mg/L	<0.01	<0.01	<0.01	<0.01	0.15
BTEX	mg/L	<0.01	<0.01	<0.01	<0.01	0.8
Microbiological Parameters						-

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Parameter	Unit	Min	Max	Average	S.D	WHO (2006)
Hydrocarbon Utilizing Bacteria	CFU/ml	0.00	0.00	0.00	0.00	0
Faecal Coliform	CFU/ml	<1.80	0.00	0.00	0.00	0
Escherichia Coli	CFU/ml	0.00	0.00	0.00	0.00	0
Total Coliform Count	CFU/ml	0.00	21.00	8.07	6.64	0
Clostridia	CFU/ml	0.00	0.00	0.00	0.00	0

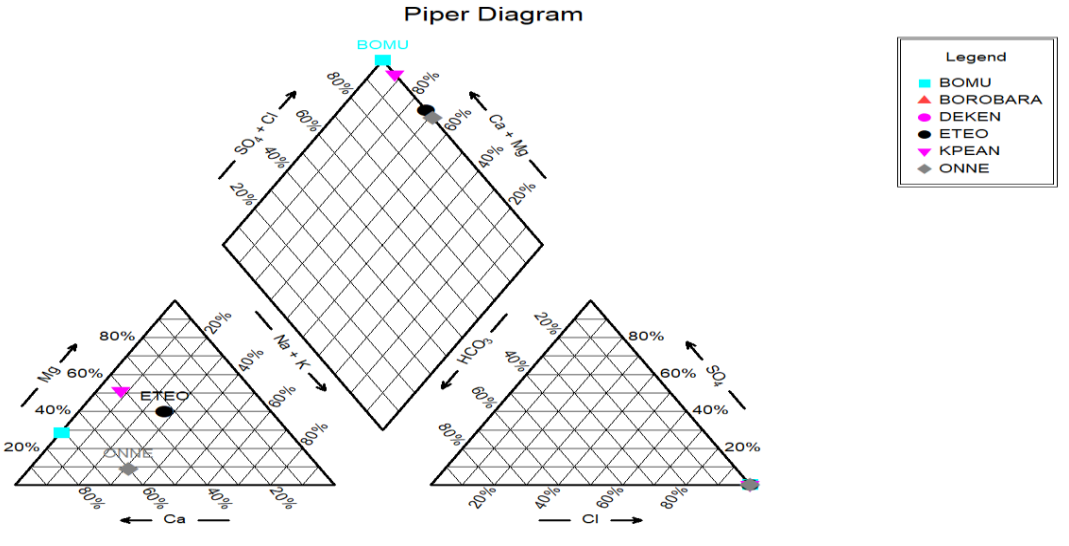


Figure 3.5: Piper diagram showing groundwater hydrogeochemistry for upper aquifer in the study area

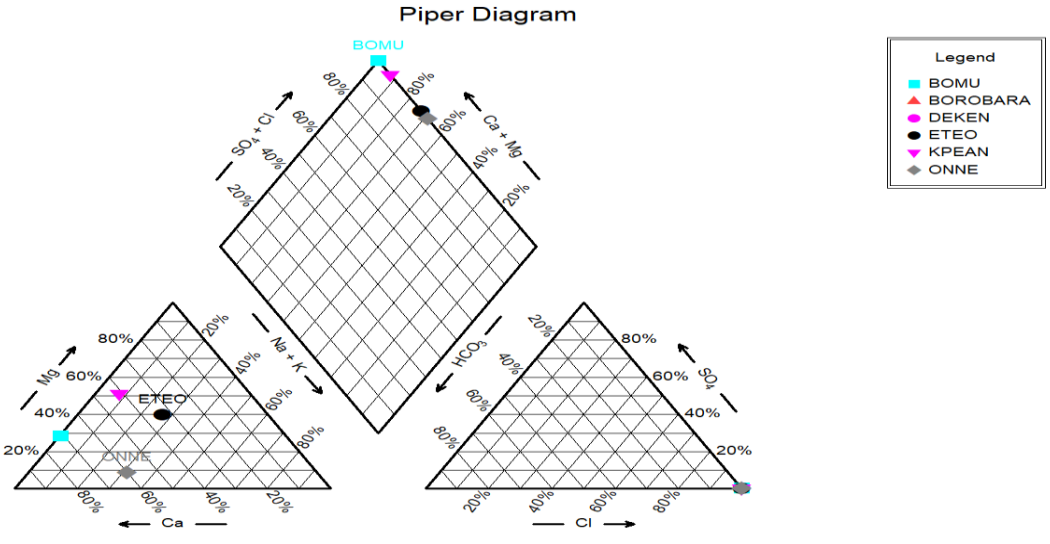


Figure 3.6: Piper diagram showing groundwater hydrogeochemistry for deep aquifer in the study area

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Table 4.3: Results of groundwater quality assessment for upper aquifer across the study area

Parameter	Unit	BOMU BH1	BOROBARA BH2	DEKEN BH2	ETEO BH2	K-DERE BH2	KPEAN BH1	KOROKORO	ONNE BH2	WHO (2006)
Physical										
Temperature, ^{O}C	^{O}C	28.9	25.1	23.00	27.00	29.10	26.76		26.82	-
Colour	TCN	1	1	0.50	1.00	1.00	1.00		1.00	-
Odour	TON	1	1	Unobj	1.00	1.00	1.00		Un-obj	-
Taste		Unobj	Unobj	Unobj	Unobj	Unobj	Unobj		Un-obj	-
Turbidity	NTU	<0.01	<0.1	0.00	<0.1	<0.01	<0.1	0.3	<0.01	5
pH		6.42	6.2	6.30	6.13	7.05	5.82	6.12	5.66	6.5-8.5
Electrical Conductivity	uS/cm	17	7	45.00	9.00	48.00	12.00	25.20	116.00	1000
Total Dissolved Solids	mg/L	8	3	22.00	4.00	24.00	6.00	12.00	58.00	500
Total Hardness	mgCaCO3/L	8	8	<0.01	4.00	6.00	2.00	10.00	10.00	300
Total Suspended Solids	mg/L	<0.001	<1		1.00	<0.001	<0.001	<0.01	<0.01	-
Chemical Oxygen Demand	mg/L	<0.01	<0.1		3.80	<0.10	<0.01		<0.1	-
Total Alkalinity	mgCaCO3/L	8	8		6.00	4.00	2.00		22.00	150
Total Acidity	mgCaCO3/L	4.00	34		18.00	<0.10	4.00		10.00	-
Cations and Anions										-
Calcium	mg/L	3.68	1.27		0.12		0.01		2.02	75
Sodium	mg/L	0.01	0.10		0.11		0.06		0.02	200
Potassium	mg/L	<0.001	<0.001		<0.001		<0.001		0.03	50
Magnesium	mg/L	0.37	0.03		0.09		0.03		0.18	-
Nitrate	mg/L	0.01	<0.001		0.02		<0.001		<0.001	50
Nitrite	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	3
Sulphide	mg/L	<0.1	<0.1		<0.1		<0.1		<0.1	250
Chloride	mg/L	1.9	<0.1		0.99		0.90		5.90	250
Free Chlorine	mg/L	<0.01	<0.01		<0.01		<0.01			-

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Parameter	Unit	BOMU BH1	BOROBARA BH2	DEKEN BH2	ETEO BH2	K-DERE BH2	KPEAN BH1	KOROKORO	ONNE BH2	WHO (2006)
Heavy Metals										
Arsenic	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	0.01
Cadmium	mg/L	<0.001	<0.001		<0.001		<0.001	<0.003	<0.001	-
Chromium	mg/L	<0.001	<0.001		<0.001		<0.001	<0.005	<0.001	0.05
Copper	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	1
Iron	mg/L	<0.001	0.03		0.08		<0.001	<0.001	1.03	0.3
Lead	mg/L	<0.001	<0.001		<0.001		<0.001	<0.002	<0.001	0.01
Zinc	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	5
Aluminum	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	0.2
Nickel	mg/L	<0.001	<0.001		<0.001		<0.001	<0.002	<0.001	-
Manganese	mg/L	<0.001	<0.001		<0.001		<0.001	<0.001	<0.001	0.2
Mercury	mg/L	<0.001	<0.001		<0.001		<0.001		<0.001	-
Hydrocarbons										
TPH	mg/L	<0.001	<0.001		<0.001	<0.001	<0.001		<0.001	50
PAH	mg/L	<0.01	<0.01		<0.01	<0.01	<0.01		<0.16	0.15
BTEX	mg/L	<0.01	<0.01		<0.01	<0.01	<0.01		<0.01	0.8
Microbiological Parameters										
Hydrocarbon Utilizing Bacteria	CFU/ml		0		0	0	0		0	0
Faecal Coliform	CFU/ml	0	0	<1.80	0	0	0		0	0
Escherichia Coli	CFU/ml	0	0		0	0	0		0	0
Total Coliform Count	CFU/ml	0	9	4.5	21	9	9		4	0
Clostridia	CFU/ml	0	0		0	0	0		0	0

Discussion

Table 3.1 shows the hydraulic characteristics of upper and deep aquifer prospects in Ogoniland. It shows a lot of spatial heterogeneity, which is a sign of the complex hydrogeology of the Benin Formation in the Eastern Niger Delta. In the upper aquifer, the

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static water levels varied from 6.44 m at Bomu to 12.88 m at Borobara, showing that the recharge and aquifer thickness were different in different places. The hydraulic heads ranged from 15.31 m at K-Dere to 261 m at Bomu, which shows how topographic gradients, aquifer connectivity, and subsurface heterogeneity can affect them (UNEP, 2011; Nwankwoala & Udom, 2020).

The upper aquifer's hydraulic conductivity (K) values also varied widely, going from 15.31 m/day at K-Dere to 264 m/day at Onne. Onne and Bomu are examples of areas with high conductivity. These areas are likely to have coarse-grained, well-sorted sand layers that can move groundwater quickly. On the other hand, areas with lower conductivity values probably have fine sediments or clay intercalations that slow down flow (Apuyor et al., 2024; Hassan et al., 2019). Transmissivity values, which combine aquifer thickness and hydraulic conductivity, show this difference even more. For instance, Bomu has a very high transmissivity of 20,880 m^2/day, which means that it is a high-yield zone that is good for municipal or industrial abstraction. On the other hand, Eteo and K-Dere have much lower transmissivity (<1,000 m^2/day), which means that they don't have much groundwater supply potential when pumping is done over a long period of time.

In the deep aquifer, hydraulic conductivity generally decreased compared to the upper aquifer, ranging from 7.92 m/day at Bodo to 264 m/day at Beeri. This is consistent with a mix of medium-to-coarse sands and semi-confining clay layers. These results corroborate earlier research characterizing the Benin Formation as a multi-layered, semi-confined aquifer system featuring discontinuous clay horizons (Ehirim & Nwankwoala, 2021; Okiwelu & Ozo, 2024). The low storativity values for both aquifers, which range from 1×10^{-7} to 5×10^{-5}, show that they don't have much room for groundwater storage and that many of the aquifer units are only partially confined (Amadi et al., 2023).

The contrasting characteristics between upper and deep aquifers have implications for water resource management. High-conductivity zones in the upper aquifer show that it can recharge quickly, but they are also more likely to get contaminated by oil spills, gas flaring, and waste disposal, which have been reported in Ogoniland (UNEP, 2011; Ikenna & Chukwudozie, 2024). Even though semi-confining layers partially protect the deep aquifer, hydraulic heads and semi-confined conditions show that vertical leakage could happen. This shows how important it is to keep an eye on things regularly to keep deeper water supplies from getting contaminated (Gbadebo et al., 2026; Apuyor et al., 2024).

The spatial variability seen is also a result of the depositional and structural controls in the Niger Delta. Coastal and transitional areas like Beeri and Taabaa have higher transmissivity and conductivity, probably because they have high-energy fluvial or paleo-channel deposits. On the other hand, inland areas like K-Dere and Bodo have lower values, which means they have low-energy depositional settings or clay-rich interbeds (Edet et al., 2014; Wokoma & Amadi, 2023). These differences are very important for designing wells that

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work well in each location, protecting aquifers, and managing groundwater in a way that is good for the environment.

In short, Table 3.1 shows that Ogoniland has a heterogeneous aquifer system, with hydraulic properties that change a lot with depth and location. To plan for sustainable groundwater extraction and protect water quality in this oil-producing area, it is important to understand these differences.

The results presented in Table 4.3 provide an in-depth assessment of the physical, chemical, heavy metal, hydrocarbon, and microbiological characteristics of groundwater within the upper aquifer across Ogoniland communities. Overall, the upper aquifer groundwater exhibits generally good quality, consistent with prior studies in the Niger Delta region (Nwankwoala & Udom, 2020; Edet et al., 2014).

Physical Parameters:

Groundwater temperatures range from 23 °C in Deken to 29.1 °C in K-Dere, reflecting normal tropical subsurface conditions. Turbidity values are exceptionally low (<0.3 NTU), indicating minimal suspended solids and high water clarity, which is typical for unconfined sandy aquifers in the region (Apuyor et al., 2024). Colour, odour, and taste were generally unremarkable, with minor variability observed in some communities, suggesting that the aquifer is largely unaffected by surface contamination. pH values vary from 5.66 in Onne to 7.05 in K-Dere, indicating slightly acidic to near-neutral conditions. Some boreholes (Kpean, Onne) exhibit pH slightly below the WHO recommended range of 6.5–8.5, potentially due to natural CO_2 dissolution in the unconfined aquifer or minor anthropogenic influence (Gbadebo et al., 2026).

Electrical Conductivity (EC) and Total Dissolved Solids (TDS):

EC and TDS values are well below WHO limits, with EC ranging from 7–116 µS/cm and TDS from 3–58 mg/L, indicating low salinity and good potability. This low ionic content reflects the dominance of coarse-grained sandy formations in the upper aquifer, which promote rapid infiltration and limited mineral dissolution (Ehirim & Nwankwoala, 2021). The low hardness (2–10 mg$CaCO_3$/L) further confirms that the aquifer is soft water dominated.

Cations and Anions:

Calcium, magnesium, sodium, and potassium concentrations are all below WHO limits, suggesting minimal geogenic or anthropogenic enrichment. Nitrate and nitrite concentrations are also very low (<0.02 mg/L), indicating negligible contamination from agricultural runoff or sewage infiltration at the time of sampling. Chloride and sulphide concentrations remain below critical thresholds, supporting the conclusion that the upper aquifer in these locations is largely unpolluted by marine or industrial intrusions. These

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findings are consistent with earlier reports on the upper Benin Formation aquifer system (Edet et al., 2014; Apuyor et al., 2024).

Heavy Metals:

All analyzed heavy metals, including arsenic, cadmium, chromium, copper, lead, zinc, aluminum, nickel, manganese, and mercury, were below WHO limits, often at trace levels (<0.001–0.08 mg/L). Iron shows minor localized enrichment (1.03 mg/L in Onne), slightly exceeding the 0.3 mg/L guideline, potentially due to natural leaching from iron-rich sediments. This pattern reflects the relatively low anthropogenic heavy metal inputs into the upper aquifer and the buffering capacity of the sandy sediment matrix (Hassan et al., 2019; Gbadebo et al., 2026).

Hydrocarbons and Organic Pollutants:

Total petroleum hydrocarbons (TPH), polycyclic aromatic hydrocarbons (PAHs), and BTEX compounds are all below WHO guideline limits for drinking water, with most values <0.01 mg/L. Minor PAH concentrations were detected in Onne (0.16 mg/L), slightly above the WHO threshold (0.15 mg/L), suggesting localized hydrocarbon infiltration from surface spills or leakage from oil-related infrastructure. This aligns with previous findings that Ogoniland aquifers are vulnerable to shallow hydrocarbon contamination due to the absence of continuous protective clay layers (UNEP, 2011).

Microbiological Parameters:

Faecal coliforms, Escherichia coli, and Clostridia counts were essentially absent (<1.8 CFU/mL), except for minor total coliform counts at Borobara, Deken, and Eteo (4.5–21 CFU/mL), likely reflecting transient surface infiltration or poorly maintained wells. The lack of significant microbial contamination indicates that the upper aquifer remains largely safe for drinking, although regular monitoring is recommended to prevent contamination during rainy seasons when surface runoff could enter hand-dug wells (Okiwelu & Ozo, 2024).

Implications for Water Supply:

The assessment confirms that the upper aquifer across most communities in Ogoniland provides potable groundwater with excellent physical and chemical quality. The slight deviations in pH and localized PAH presence highlight the need for targeted water quality monitoring, especially near oil infrastructure or surface contamination sources. These findings support sustainable use of the upper aquifer for domestic, agricultural, and limited industrial purposes while emphasizing that deeper aquifers may require additional investigation for long-term abstraction planning.

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In conclusion, the upper aquifer in Ogoniland demonstrates low contamination levels, soft water conditions, and minimal heavy metal burden, reflecting both favorable hydrogeological conditions and relatively limited anthropogenic stress at the time of sampling. Continuous monitoring and community-level water safety practices are recommended to maintain this quality and prevent episodic contamination.

The Piper diagram interpretation provides critical insight into the hydrochemical evolution and controlling processes of groundwater within both the upper and deep aquifers across Ogoniland. The results indicate a clear dominance of the calcium–chloride (Ca–Cl) water type throughout both aquifer systems, reflecting the combined influence of marine-derived salinity, geogenic processes, and limited anthropogenic impact. In the Piper plots, most samples cluster toward the Ca^{2+}–Mg^{2+} region in the cation triangle and the Cl^- apex in the anion triangle, confirming that alkaline earth metals dominate over alkali metals while chloride is the principal anion. This hydrochemical signature is characteristic of coastal sedimentary aquifers and is commonly associated with processes such as ion exchange, water–rock interactions, and residual seawater influence (Adimalla & Qian, 2019; Ukah et al., 2020).

The prevalence of Ca–Cl water across both shallow and deep aquifers suggests that groundwater chemistry is strongly influenced by a combination of geogenic and marine processes. In coastal deltaic settings such as Ogoniland, chloride enrichment often arises from seawater intrusion or connate marine water retained in sedimentary formations (Egbueri & Unigwe, 2020). The higher chloride concentrations observed in southern communities, including Bodo and Onne, relative to northern locations such as Beeri and Uegwere, indicate a clear salinity gradient trending toward the Bonny River and associated tidal creeks. This observation aligns with regional studies highlighting early-stage saline intrusion in aquifers near estuarine systems (Ukah et al., 2020; Apuyor et al., 2024).

Elevated calcium concentrations in both aquifers may reflect geochemical processes such as the dissolution of calcareous materials and cation exchange. In clay-rich zones, sodium adsorbed on clay minerals can be replaced by calcium in groundwater, leading to the development of the Ca–Cl facies. The discontinuous clay layers separating the upper and deep aquifers in Ogoniland facilitate this ion exchange while allowing limited vertical mixing between aquifer units, consistent with observations in similar sedimentary basins (Subba Rao et al., 2017; Adimalla & Qian, 2019).

The hydrostratigraphic framework further explains the observed hydrochemical patterns. Although semi-confining clay layers are present, their discontinuity permits hydraulic connectivity between aquifers, enabling partial vertical mixing of groundwater. This mechanism likely accounts for the similar hydrochemical signatures observed in the upper and deep aquifers despite differences in depth. Recent studies in coastal deltaic

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environments have emphasized that semi-confined systems frequently display overlapping water types due to recharge and leakage through permeable zones (Egbueri et al., 2021).

Physicochemical data from the study support these interpretations. Calcium (0.01–3.68 mg/L) and magnesium (0.03–0.37 mg/L) concentrations are generally low, indicating limited mineralization, while chloride variability (0.05–5.90 mg/L) reflects localized salinity influence. Electrical conductivity (7–116 µS/cm) and total dissolved solids (3–58 mg/L) are low, suggesting fresh groundwater with early signs of chemical evolution in southern and coastal locations. These trends correspond with findings from recent coastal aquifer studies reporting low TDS alongside increasing chloride content as an indicator of early-stage saline influence (Egbueri & Unigwe, 2020).

Slightly acidic to near-neutral pH values (5.66–7.05) may result from organic matter decomposition and carbon dioxide dissolution, which are common in shallow aquifers. Elevated iron levels, particularly at Onne (1.03 mg/L), are likely associated with reducing conditions and the dissolution of iron-bearing minerals, a feature often observed in deltaic sediments (Ukah et al., 2020). Low nitrate levels (<0.001 mg/L) across all locations suggest minimal agricultural or sewage contamination, highlighting the limited anthropogenic nutrient impact in the study area.

Overall, the hydrochemical characteristics indicate that Ogoniland's groundwater is primarily governed by natural geochemical processes—including mineral dissolution, ion exchange, and residual marine influence—with some contribution from vertical mixing between aquifers. The dominance of Ca–Cl facies, particularly in southern and deeper aquifers, underscores the system's susceptibility to saline intrusion and the controlling influence of the coastal hydrogeological setting. These findings are consistent with recent hydrogeochemical assessments in the Niger Delta and other coastal sedimentary environments, which emphasize the integrated roles of geology, hydrodynamics, and marine processes in shaping groundwater chemistry.

Conclusion

This study offers a thorough assessment of the hydrogeological framework and groundwater quality of upper and deep aquifer systems in Ogoniland, Southern Nigeria, uncovering a complex, heterogeneous, and semi-confined aquifer system characteristic of the Benin Formation in the Niger Delta. Using borehole lithologic data and downhole logs to define aquifer intervals shows that there are two aquifer units: an upper (shallow) aquifer and a deeper aquifer. These two aquifer units are separated by a clay layer that is not continuous in the horizontal direction. This hydrostratigraphic arrangement encourages partial hydraulic connectivity, facilitating vertical recharge and interaction

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among aquifer systems, while simultaneously heightening susceptibility to contaminant migration.

Hydraulic characterization reveals considerable spatial variability in aquifer properties throughout the study area. The upper aquifer has moderate to high hydraulic conductivity (15.31–264 m/day) and transmissivity (371–20,880 m^2/day) because it is mostly made up of sand and can hold a lot of water. The deep aquifer, which is made up of medium to coarse-grained sands, has a hydraulic conductivity (7.92–264 m/day) and transmissivity (158.39–7,776 m^2/day) that are both very different but generally high. This means that it can store and yield a lot of groundwater. The storativity values for both aquifers (10^{-4}–10^{-7}) show that they are only partially confined, which is in line with the fact that there are discontinuous confining layers. The aquifers having similar hydraulic heads is more proof that vertical hydraulic interaction and groundwater flow are both happening in the system.

Patterns of groundwater flow based on elevation and hydraulic head distributions show a regional gradient from the northern upland areas to the southern low-lying areas and river systems, especially the Bonny River and its tributaries. This flow regime controls how the aquifer system gets recharged, how contaminants move through it, and how salt is spread throughout it.

Hydrochemical analysis indicates that groundwater in both aquifers is predominantly fresh, soft, and characterized by low mineralization, with the majority of physicochemical parameters conforming to acceptable drinking water standards. The calcium–chloride (Ca–Cl) hydrochemical facies are the most common in both aquifers. This shows that marine processes, leftover saline water, and geochemical interactions like ion exchange have an effect. A clear spatial trend of higher chloride levels in southern coastal communities shows how close they are to tidal systems and how early-stage saline intrusion might happen.

The levels of heavy metals and hydrocarbons are mostly below the limits set by the law, which means that there was probably not a lot of widespread contamination at the time of the study. Localized anomalies, including heightened iron levels and slightly increased polycyclic aromatic hydrocarbons (PAHs), suggest site-specific effects likely associated with natural geochemical conditions and human activities, such as oil exploration and related operations. Microbiological testing shows that the contamination levels are generally low. However, the presence of total coliforms in some areas suggests that there may be occasional surface infiltration, especially in the upper aquifer.

The study shows that the groundwater resources in Ogoniland are mostly still good for farming and living, but the aquifer system is naturally weak because it is only partially confined, has hydraulic connections, and is close to sources of pollution. The interaction

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of hydrostratigraphy, hydraulic properties, and hydrochemical processes shows that different sites need different ways to manage groundwater.

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