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QUALITATIVE CHARACTERIZATION OF DELINEATION OF UPPER AND DEEP AQUIFER INTERVALS AND VERTICAL VARIATION OF GROUNDWATER QUALITY IN OGONILAND, NIGER DELTA, NIGERIA

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Abstract

Groundwater remains the primary source of potable water in Ogoniland, located within the Niger Delta of southern Nigeria, where increasing anthropogenic activities particularly oil exploration, waste disposal, and urbanization pose significant threats to water quality. Understanding the vertical variation in aquifer characteristics and groundwater chemistry is therefore essential for sustainable water resource management. This study assessed aquifer characterization and groundwater quality variation across depth in Ogoniland, with the aim of evaluating hydrostratigraphic conditions, hydraulic properties, and hydrochemical processes influencing groundwater systems. A combination of field and laboratory methods was employed. Boreholes were drilled using rotary drilling techniques, followed by wireline and manual logging to delineate lithology and aquifer boundaries. Pumping tests were conducted to determine hydraulic parameters such as hydraulic conductivity, transmissivity, and storativity. Groundwater samples were collected from both shallow and deep aquifers and analyzed for physical, physicochemical, and microbiological parameters using standard laboratory procedures. Hydrochemical facies were determined using Piper diagram analysis, while water quality was evaluated using the Water Quality Index (WQI). Results

Keywords:
Groundwater quality, Aquifer characterization, Hydrogeochemistry, Calcium–chloride facies, Niger Delta, Ogoniland

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revealed significant spatial and vertical variability in aquifer characteristics. The upper aquifer thickness ranged from 15 m to 80 m, while the deep aquifer varied from 20 m to 85 m. The depth to the top of the deep aquifer ranged widely from 16.00 masl to 109.27 masl, indicating strong heterogeneity in subsurface conditions. Hydraulic conductivity values ranged from 15.31 to 264 m/day in the upper aquifer and 7.92 to 264 m/day in the deep aquifer, while transmissivity varied from 371 to 20,880 m^2/day and 158.39 to 7,776 m^2/day, respectively. Storativity values (10^{-4} to 10^{-7}) confirmed semi-confined conditions in both aquifers. Hydrochemical analysis showed that groundwater is predominantly of the calcium–chloride (Ca–Cl) type, indicating the influence of marine processes, ion exchange, and water–rock interactions. Physicochemical parameters revealed generally low mineralization, with total dissolved solids ranging from 3 to 58 mg/L in the shallow aquifer and 2 to 38 mg/L in the deep aquifer. Electrical conductivity ranged from 7 to 116 µS/cm, while pH values varied between 5.50 and 7.25. Chloride concentrations ranged from 0.05 to 9.77 mg/L, with higher values observed in coastal communities such as Bodo and Onne, suggesting saline influence. Most heavy metals were below detectable limits, although elevated iron concentrations (up to 1.026 mg/L) were recorded in some locations. Microbiological analysis showed minimal contamination, with no detection of *E. coli* and only moderate total coliform presence in a few shallow wells. The Water Quality Index classified most groundwater samples as "excellent," with only isolated cases of reduced quality. The study concludes that groundwater in Ogoniland is generally of good quality but is influenced by complex hydro stratigraphic conditions and is vulnerable to contamination due to the semi-confined nature of the aquifer system and the absence of a continuous protective clay layer. Vertical hydraulic connectivity between aquifers increases the risk of contaminant migration, particularly in areas affected by oil-related activities. It is recommended that groundwater protection strategies be strengthened through regular monitoring, proper siting and design of boreholes, and control of pollution sources. Protection of recharge zones and enforcement of environmental regulations in oil-producing areas are essential. Further studies should incorporate long-term monitoring and advanced contaminant tracing techniques to better understand groundwater dynamics and ensure sustainable water resource management in the region.

Introduction

A higher level of life depends on having access to safe drinking water, which is also a key objective of sustainable water resources management under water supply sanitation and hygiene (WASH) (Hutton and Chase, 2016). Water is a clear liquid

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that is widely available on Earth. One oxygen atom and two hydrogen atoms make up a water molecule. All living things are built on water. For plants, animals, and humans to survive, water is a necessary natural resource. Humans cannot live long without water since it is essential to the healthy operation of all of the body's cells and organ systems. Water is essential to all biological processes, either directly or indirectly. All of the body's functions are powered by water. In many developing countries, access to sufficient, clean drinking water is a significant issue in both rural and urban regions. In rural places, groundwater provides a reliable but constrained source of water. The most widely used water sources for agriculture and other uses are groundwater and surface water. Water, which can be either surface or groundwater, is one of the most important natural resources. All life as we know it depends on it. Having access to and consuming enough water is essential to the progress of our society. This precious resource is distributed unevenly in space and time, appearing abundant at times and scarce at others.

Since water quality is closely related to human welfare, it is a major concern for all of humanity (Balkrishnan et al., 2011). Unfortunately, improper landfill and waste disposal, excessive fertilizer usage, unsanitary conditions, and rapid urbanization have all put groundwater quality at jeopardy. Therefore, in many parts of the world, pollution from both natural and man-made causes has put human health at risk (Akporido, 2008). Mitra and Roy (2011) emphasized that heavy metals (such as zinc, copper, chromium, nickel, cadmium, lead, and mercury) can contaminate groundwater through landfill leaks and industrial discharges from chemical and metallurgical companies.

The class of organic pollutants known as "benzene, toluene, ethylbenzene, and xylenes" (BTEX) include xylene, benzene, toluene, and ethylbenzene. Petroleum products like as gasoline, die-sel fuel, lubricating oil, and heating oil can leak from oil tanks and contaminate or pollute soils with volatile organic compounds (VOCs) (Sa-lanitro et al., 1997; Nwankwoala, 2014). BTEX have received a lot of attention lately because they are among the most common and serious threats to indoor climates and groundwater reservoirs that come from contaminated sites (Uzoekwe and Oghosanine, 2011). This is mostly due to the potential effects of benzene, which is thought to be a major carcinogen and is highly mobile in soil and groundwater habitats. Activities involving the use of gasoline, kerosene, and heating fuel that have high concentrations of BTEX can create pollutants. BTEX are important pollutants and contaminants that have attracted a lot of attention because of their high water solubility and toxicity. Blood problems, cancers, mucosal pain, harm to the respiratory and central neurological systems, and problems with liver and kidney function can all result from BTEX (Li and Zhou, 2011; Nourmoradi et al., 2012). China's top blacklist of pollutants that require prompt control includes six benzene series, including BTEX (Cheng, 2016).

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The second most plentiful freshwater resource in the world, groundwater, contains around 30% of all freshwater resources. Groundwater comes from the water cycle because precipitation is followed by surface runoff and percolation, which refuel underground aquifers.

Most people agree that groundwater is a reliable supply of pure freshwater that can be used for agriculture, industry, and drinking. Groundwater can also be replenished by natural surface water bodies and artificial sources due to human activity.

An essential natural resource, groundwater is incredibly valuable to humans and other living things. Applications include home, industrial, and irrigation uses. Aquifers are holes and fissures in rock that contain liquid below the surface. This liquid is known as groundwater. Groundwater, which supplies an estimated 36% of home water, 42% of agricultural water, and 27% of industrial water used globally, accounts for one-third of all freshwater withdrawals. Due to its ease of exploration and low infrastructure requirements, groundwater use is encouraged to expand broadly in order to meet the necessary water demand (Taylor, et al., 2012).

One important natural source of drinking water is groundwater. Although groundwater's chemical and biological characteristics are suitable for most applications, human activity has altered the groundwater's quality (Gajendran and Thamarai, 2008; Horton, 1965). The natural quality of groundwater varies as it flows from springs, rivers, and recharge areas. The majority of common dissolved mineral components, including bicarbonate, chloride, calcium, magnesium, sodium, and potassium, are found in groundwaterAs groundwater flows from springs, rivers, and recharge regions, its natural quality fluctuates. The majority of common dissolved mineral components, including bicarbonate, chloride, calcium, magnesium, sodium, and potassium, are found in groundwater (Ryznar John, 1986). The amount of organic molecules and dissolved minerals in groundwater determines its fitness for a certain usage, among other things. While some components are benign, some are toxic, and a tiny percentage may be exceedingly dangerous (Parihar, et al., 2012). One of the primary reasons for the increase in solid waste levels is population growth. Agriculture has a significant impact on groundwater quality where intensive practices are applied. Unwanted man-made items have the potential to contaminate groundwater and render it unsafe for human consumption. The health effects of groundwater pollution could be extremely detrimental. Pollutants have long been thought to occur both above and below earth (Kumar and Ahmed, 2003; Kaplay and Patode, 2004). Groundwater flow and aquifer dispersion spread the pollutants across a greater area. Surface water gathers minerals, salt, and organic matter as it percolates into the soil. As water descends, the concentration of dissolved solids rises. In some areas, mineral concentrations are high enough to make groundwater unfit for drinking and irrigation without treatment. When contaminated water seeps into the ground and

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reaches an aquifer, it is considered ground water contamination (Meena, et al., 2001; Mohan, et al., 2010).

The entire quality of groundwater is determined by its physical, chemical, and biological properties. The physical, chemical, and biological characteristics of groundwater define its overall quality. Temperature, turbidity, color, taste, and odor are some of the physical characteristics of water quality. Since the majority of ground water is colorless, odorless, and tasteless, we are typically mainly concerned about its chemical and biological characteristics. By nature, ground water contains mineral ions. These ions are gradually dissolved from rocks, sediments, and soil particles by water passing through the aquifer's pores and fissures in the unsaturated zone. They are referred to as dissolved solids. The aquifer may have been replenished by precipitation water or the river, which may have contributed part of the dissolved solids.

Groundwater is defined as fresh water that seeps into the soil and gets trapped in the pore spaces, fissures, and cracks of rocks and other geological formations. It may come from rain or from snow and ice melting. Numerous geological formations contain groundwater; the textural arrangement of these formations dictates how much water they can hold. In most cases, the source of groundwater can be determined to be surface runoff and rainfall that seeps into subterranean streams and lakes. This water table serves as the main supply of water for bays, lakes, streams, and seas. The textural organization of most rocks and geological formations, whether it be loosely organized or uniformly packed, greatly affects the rock's or geological formation's capacity to hold onto water. "Aquifer" is a name used to describe any geological formation that has certain characteristics. Geological formations or rocks with a homogeneous or closely packed texture have a high porosity but a low permeability, or the capacity to transfer or move water. Higher porosity and permeability, on the other hand, contain enough of both to provide wells and springs with sizable amounts of groundwater. An aquifer is any underground rock layer or geological formation that has sufficient water to sustain springs and wells. A body of saturated rock that facilitates the easy storage and transport of groundwater is called an aquifer. Aquifers can be found at varying depths, although those nearer the surface are more likely to be used for irrigation and water distribution, as well as being refilled by surrounding rainfall. In geological terminology, an aquifer is a body of saturated rock or other geological structure that allows water to pass through wells and streams with ease (permeability). The water's highest position in an aquifer is called the water table. Rain or melted snow can cause water to seep into the ground, filling an aquifer. In certain locations, water may enter the aquifer through the soil; in other locations, it may enter through the joints and fissures in the rock and move downward until it reaches less permeable materials. Generally regarded as reservoirs,

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aquifers may dry up if human activity depletes them faster than the pace of natural replenishment.

The Niger Delta is now Nigeria's economic center due to the exploration of crude oil there. As a result of the region's attraction to the many petrochemical and petroleum businesses, both urban and rural-urban migration have increased. The region's water resources are being strained by the expanding population (Edet, et al., 2014).

The groundwater quality in this area has been significantly deteriorated by complicating factors such as flooding, gas flaring, and oil spills (Nnabuenyi, 2012), thereby raising the cost of soil, groundwater, and surface water resource cleanup for Nigeria's federal government. All of the states that border the River Niger and its tributaries experience floods each year, but it is more common in the states of Delta, Bayelsa, and Rivers. Disasters brought on by these floods episodes are also connected to climate change (Gordon and Obenade, 2015; Mmom, 2012). 111 municipalities, totaling over 7 million residents, are hence vulnerable to flooding (Gordon and Obenade, 2015).

The majority of the groundwater in the Niger Delta is found in aquifers that are primarily made of large, heavy sand and gravel. It is possible to identify three primary zones. These consist of the transition zone, which combines continental and marine elements, the northern bordering zone with shallow aquifers predominantly made of continental deposits, and the coastal zone with mostly marine deposits (Etu-Efeotor and Odigi, 1983; Amajor, 1989, Etu-Efeotor and Akpokodje, 1990). Since this break, a clear pattern in the properties of the aquifer has been noted. Akpokodje et al. (1996) Four distinct aquifers, ranging in thickness from more than 120 meters, have been found in the upper 305 meters to indicate the hydro stratigraphic units of the Benin Formation. While unconfined conditions are seen at the surface, conditions in the aquifers range from semi-confined to confined at depth. Since the aquifers are separated by extremely uneven shale strata, the region between them forms a complex, non-uniform, discontinuous, and diversified aquifer system. Although most groundwater supply wells in the Benin Formation derive their water from these aquifers, there is evidence that local municipal and industrial groundwater supply wells also receive water from deeper aquifers.

The aquifers on the northern edge of the Niger Delta have a more continental character due to river loads from the hinterland. Additionally, because they are found at lesser depths, drilling down to an average depth of 60 meters may typically recover enormous amounts of wonderfully clean freshwater. Except for a few meters present in the top soil, clay materials are absent at depths. Layers of gravel are occasionally visible, and the sand is often coarse to extremely gritty. Drilling wells in the northern Niger Delta's borders has long been taken for granted due to the region's traditionally excellent water quality and borehole performance. In the eastern Niger Delta, the Port Harcourt, Ogoni, and Elele regions of Rivers State are prime examples of this type of environment.

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The soil structure of Ogoniland has a major role in determining how much pollution can go downward and seep underground. It was once believed that Ogoniland had a clay layer that shielded the community's drinking water from oil pollution. As a result, Ogoniland's oil cleanup approach only addressed the uppermost layers. Nonetheless, the data gathered from 780 boreholes as part of UNEP's assessment may provide an accurate definition of the soil's properties in Ogoniland. The main conclusion is that Ogoniland does not have a continuous clay layer, which facilitates the easy descent of hydrocarbons that are spilled on the top. In 49 cases, UNEP discovered hydrocarbons in soil that was at least five meters below the surface. The type of remedy that is required will be significantly impacted by this revelation.

The drinking water for everyone in Ogoni comes from subterranean aquifers. Protecting this groundwater supply is crucial because of this. According to the geological profile of the area, Ogoniland has only one aquifer, which is being used by both shallow wells and deeper boreholes. Ogoni communities typically excavate wells by hand and then utilize pumps or manual labor to extract the water. In Ogoniland, UNEP drilled 180 groundwater monitoring wells as part of the review process. At its deepest point, the recorded water level was 14 meters below the surface, with a range of 0.7 meters below the surface. According to the study, hydrocarbons that seep to the surface may pollute the Ogoni community's drinking water supply. Hydrocarbons were found in drinking water samples from 28 wells in ten villages near hazardous areas. The locals say they have no choice but to use the water despite being aware of the pollution. In certain contaminated places, communities search for pure water by drilling deeper wells up to 30 meters deep. However, the UNEP assessment found that this approach is not a sustainable solution because a deeper excavation could inadvertently hasten the vertical spread of the contamination.

Oil extraction and other activities have caused major environmental issues in Ogoniland, a region in the Niger Delta of Nigeria. Investigating the aquifer's properties in relation to groundwater quality in Ogoniland is crucial since these activities frequently result in contamination and deterioration of groundwater resources, which negatively affect the health and well-being of local populations. Understanding the differences in groundwater quality in the Ogoniland region, especially with regard to varying aquifer system depths, is likely to be the main focus of this study.

Study Area

Ogoniland is in the southern Nigerian region of the Easthern Niger Delta, in Rivers State, east of Port Harcourt, and close to the Gulf of Guinea coast. inhabit a habitat that is 1,050-square-kilometer (404-square-mile) in size, the third biggest mangrove ecosystem in the world, and have a population of about 832,000 (based on the 2006 National Census). On

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the Greenwich meridian, the Ogoni region is situated between latitudes 511510–524485 and longitudes 300830-328331. Four local government areas of the state rivers make up the administrative division of Ogoniland. The Ogoni people are primarily farmers and fishermen.

This study was carried out in Ogoniland's four local government districts.

Eight boreholes were dug in each of Ogoniland's local government areas, ranging in depth from 20 to 150 meters. At different depths within the local aquifer, the boreholes were screened.

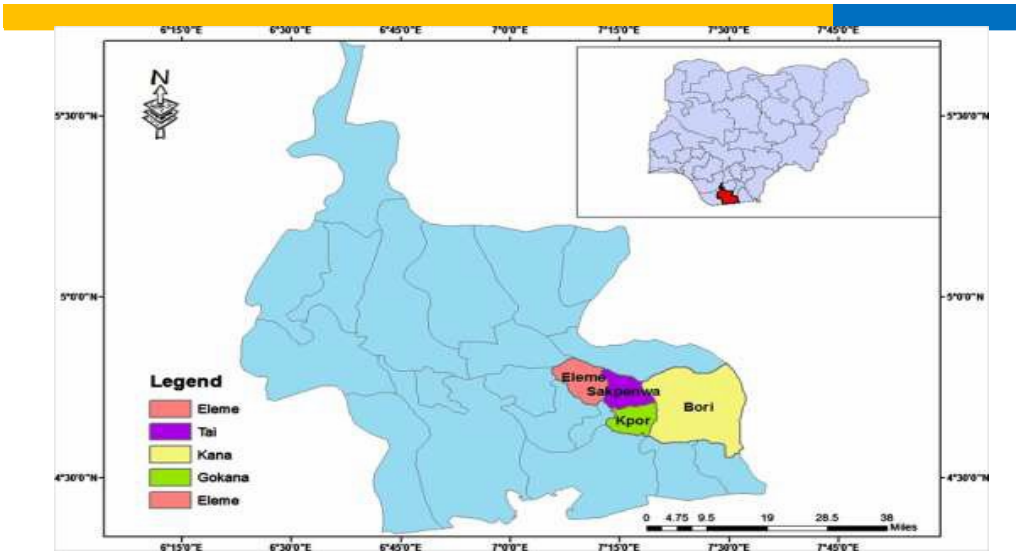


Figure 2.1: Map of Rivers State Showing Study Area

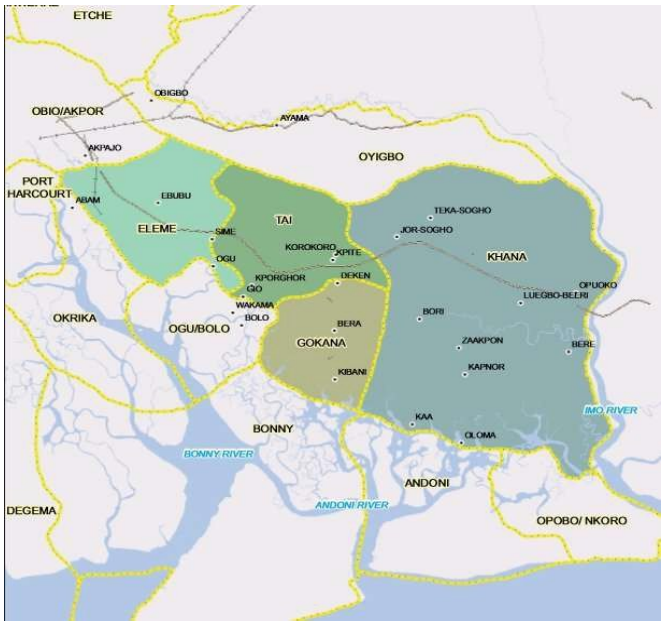


Figure 2.2: Map of Study Area

Study Design

Drilling, Logging, Aquifer Testing, and Water Quality Assessment

The study utilized a comprehensive hydrogeological and water quality assessment framework, incorporating borehole drilling, logging, aquifer evaluation, and laboratory analysis. The rotary drilling method was used to drill the

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boreholes. This method uses drilling mud (a mixture of water, bentonite, and additives) to help the drill bit get through, cool it down, and keep the walls of the borehole stable. It also moves cuttings to the surface. This technique works best for deep boreholes and formations that aren't solid.

Both wireline logging and manual logging were used to characterize the subsurface. Wireline logging involved lowering instruments into the borehole to get continuous in-situ data on formation properties like resistivity, porosity, and gamma radiation. Manual logging, on the other hand, gave direct observations of lithology, depth, water levels, fractures, and drilling performance. These methods worked together to make sure that the aquifer characteristics were correctly identified.

Using the right well screens, boreholes were screened in both shallow and deep aquifer zones. This let water in but kept sediment out. Gravel packing was used to improve filtration and the stability of the borehole. A 24-hour constant head pumping test was done to find out the aquifer's hydraulic properties. During the test, water levels and discharge rates were watched to find out transmissivity, hydraulic conductivity, and storativity.

To check the quality of the water, samples were taken from the boreholes in a systematic way and then analyzed in a lab for physical, physicochemical, and biological parameters. We measured things like temperature, turbidity, color, taste, and smell. We also did physicochemical tests, which looked at things like pH, electrical conductivity, total dissolved solids, nutrients, and heavy metals. Biological analysis concentrated on indicators like E. coli and coliform bacteria. To make sure the results were correct, standard analytical methods like titrimetric and spectrophotometric methods were used. Lastly, hydrogeological and water quality data were combined to find connections between aquifers and look at how groundwater quality changes across the study area.

Method of Solution for Data Analysis

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

Following Abel and Tosin (2019), a limited region of contaminated water where contaminants are concentrated is referred to as a pollutant plume in groundwater. This region can be compared to a "cloud" or "stack" of tainted water flowing through the aquifer. These plumes can spread over time as groundwater flows and are frequently the result of contaminants being released from a single source, such as an inadequately managed landfill or a leaking underground storage tank.

Images of the plumes of source pollutants resemble what the human eye sees. Though their boundaries are clearly defined, each plume wiggles left and right and up and down. Through such an immediate pollution plume, the concentration of C might vary greatly.

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The majority of the contaminants are located close to the plume's centerline. As one moves farther from the centerline, the average concentration gradually drops. The concentration profile that results is frequently Gaussian or bell-shaped.

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):

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

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

It is challenging to locate the margins of time-average plumes. Because the bell curve progressively becomes closer to zero concentration as one gets farther away from the midline, they are not well defined. As a result, edges cannot be used to gauge the depth or width of plume spread. Rather, plume spread is measured using the standard deviation δ_z of the pollutant location, where standard deviation is the square root of the variance δ_z^.2. Sigma must be calculated by weighting the vertical-position deviations by the pollutant concentration (Okaba and Akpodee, 2024):

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

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:

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

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:

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

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:

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

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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:

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

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:

Well-Posedness

The problem is well defined if the evolution equation has the proper number of initial (or boundary) conditions for its solution; it is well posed if the solution is distinct, existent, and is continuously reliant on the original data. A model for a certain physical system's main objective is to predict the system's behavior over a predefined time period, beginning with the condition at the initial time to. The starting value problem is subsequently resolved to get the model's predictions. A problem must meet a few fundamental criteria in order to do that:

- At least for the appropriate amount of time, the answer should be available.
- It should be a distinctive solution.
- One should expect that the impact of a small mistake made in describing the current situation will be negligible in the future. This is because the solution should be continually dependent on the original data and the model's parameters. As previously mentioned, the initial-value problem is considered well posed if these conditions are met.

Numerical Iterations Mathematical Preliminaries

Following Akpodee (2019), when analytical solutions are not available for initial value problems (IVPs), numerical methods must be employed. As part of the mathematical preliminaries, we have only taken into consideration the widely used fourth-order Runge-Kutta method among the numerical techniques available for handling initial value problems. The following is a presentation of this method's theoretical definitions and mathematical structure:

An accurate and adaptable approach to the initial value problem, the fourth-order Runge-Kutta (R-K) method is based on a Taylor series approximation to the function f(x,y).

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

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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

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

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,

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

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$$k_3 = hf(x_n + \frac{1}{2}h\ ,\ y_n + \frac{1}{2}k_{2,}z_n + \frac{1}{2}K_2)$$
$$k_4 = hf(x_n + h\ ,\ y_n + k_3,\ \ z_n + K_3)$$

and

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

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 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: Delineated Upper Aquifer and Deep Aquifer intervals based on borehole lithlogic data and Downhole Logs

Community	Northing (mN)	Easting (mE)	Top to Upper Aquifer (masl)	Shallow Aquifer thickness (m)	Top to Deep Aquifer (masl)	Deep Aquifer Thickness (m)
Bomu	511510	312276	9.00	40	54.00	80
Borobara	523668	304933	10.00	70	83.66	30
Deken	520945	311457	16.00	60	87.41	60
Eteo	524802.82	298856.63	16.72	80	108.20	20
K-Dere	515111.6	307995.2	9.00	15	32.26	65
Onne	522899.21	295228.9	8.55	50	71.83	45
Taaba	523571	325380	10.00	45	16.00	50
Beeri	518771	325333	6.00	24	42.86	85
Bodo	512894.5	308673.5	10.00	20	29.58	60
Barayira	524466.8	300872	15.00	75	102.73	20
Ebubu	528743.51	294765.31	17.61	75	109.27	35
Kporghor	520679.53	303534.92	6.00	60	77.81	40
Kpean	510638.4	328346.89	10.00	60	82.41	55
Uegwere	513285	317967	27.83	60	86.21	40
Korokoro	523749.9	312544.56	22.10	45	98.20	50

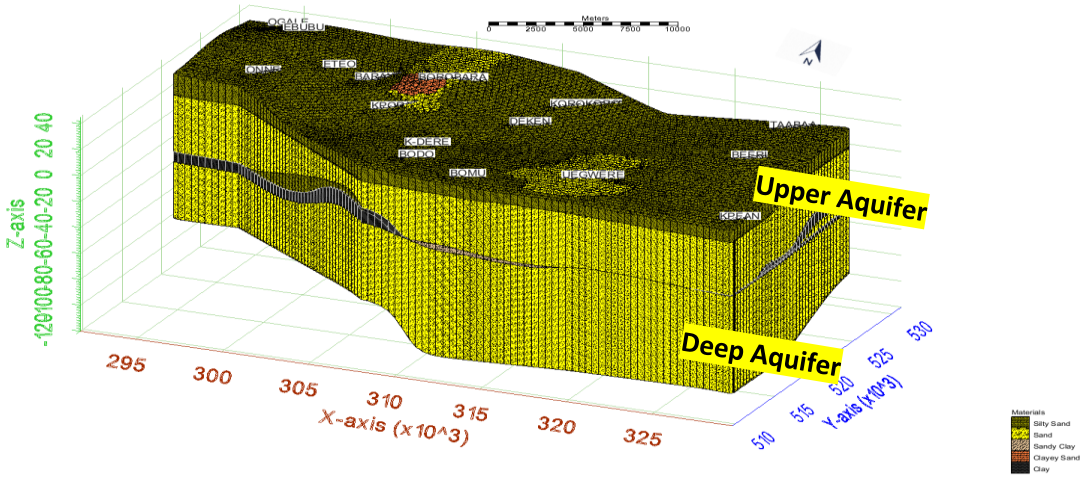


Figure 3.1: 3-D lithologic model showing soil types and aquiferous bodies across the study area

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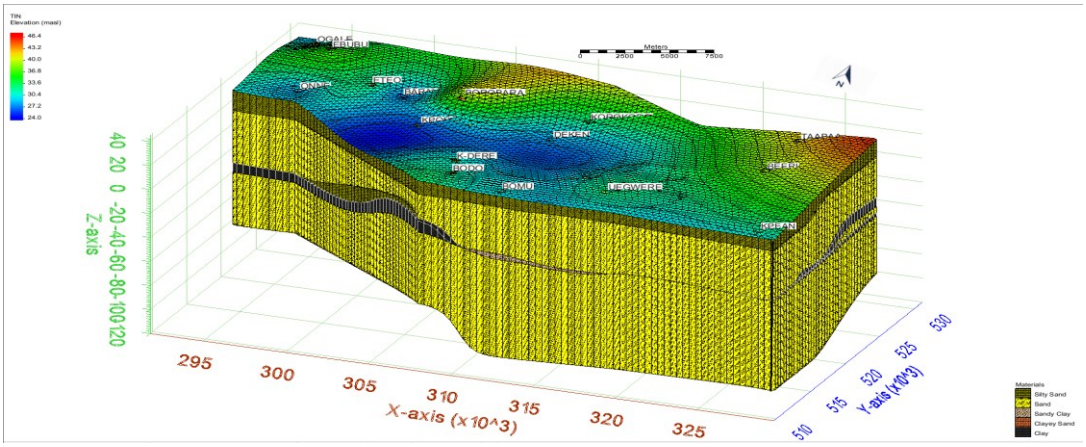


Figure 4.2: 3-D lithologic model showing soil types and aquiferous bodies across the study area along with topographic overlay

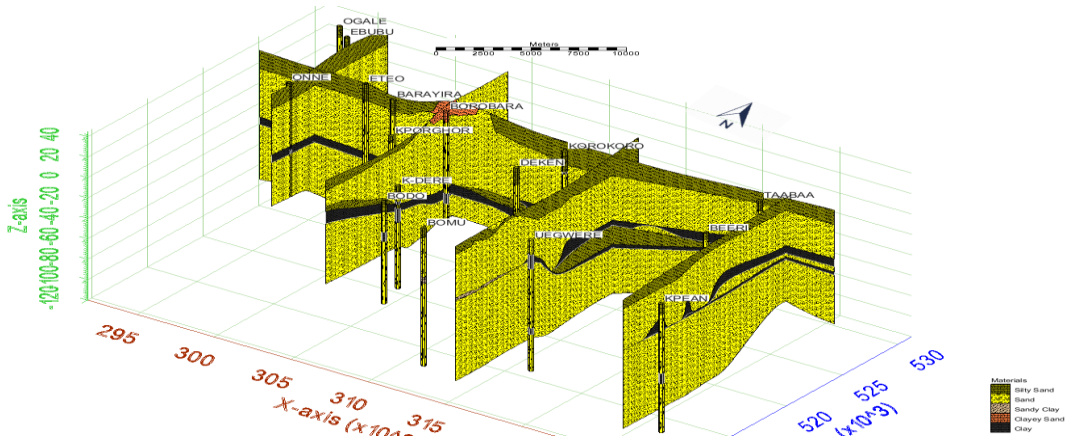


Figure 4.3: Fence diagram showing lithologic variation across the study area

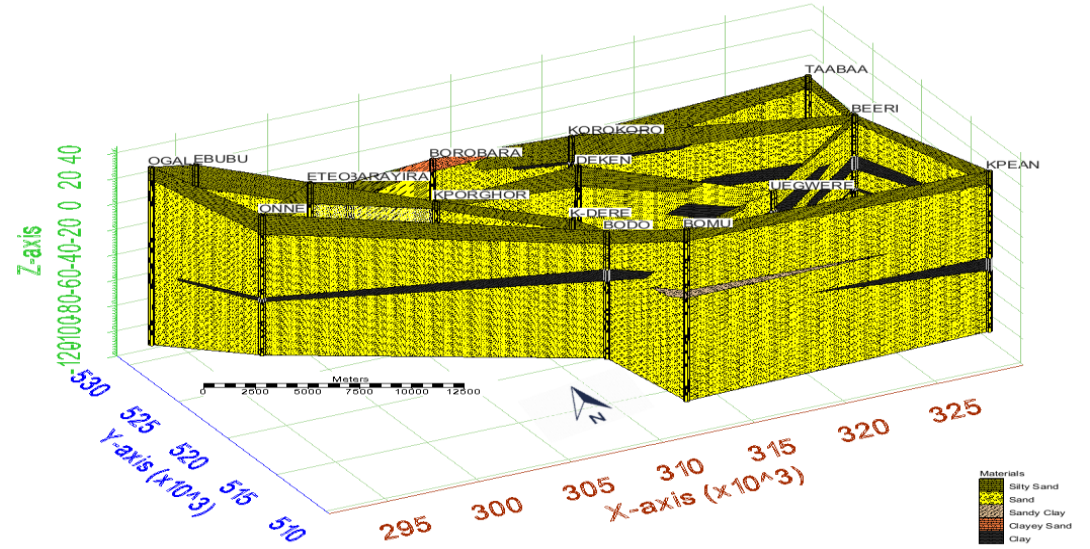


Figure 4.4: Fence diagram showing lithologic variation across the study area

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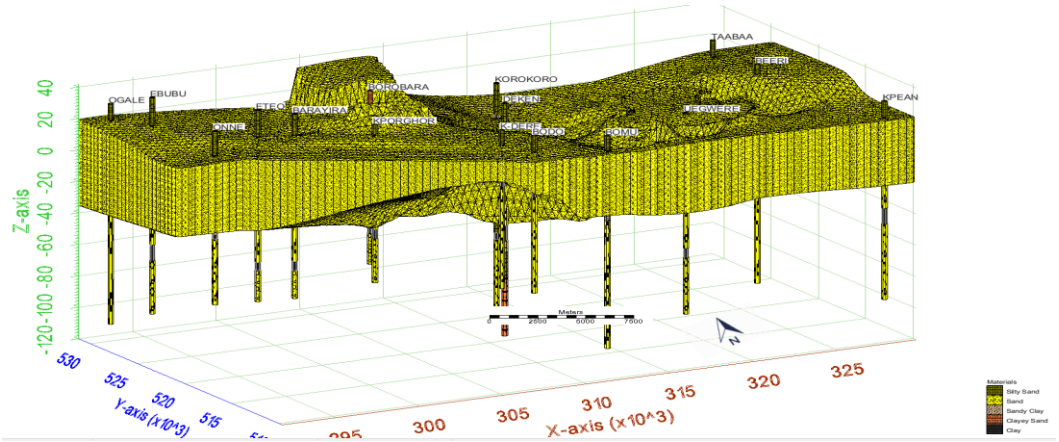


Figure 4.5: Delineation of Upper Aquifer across the study area

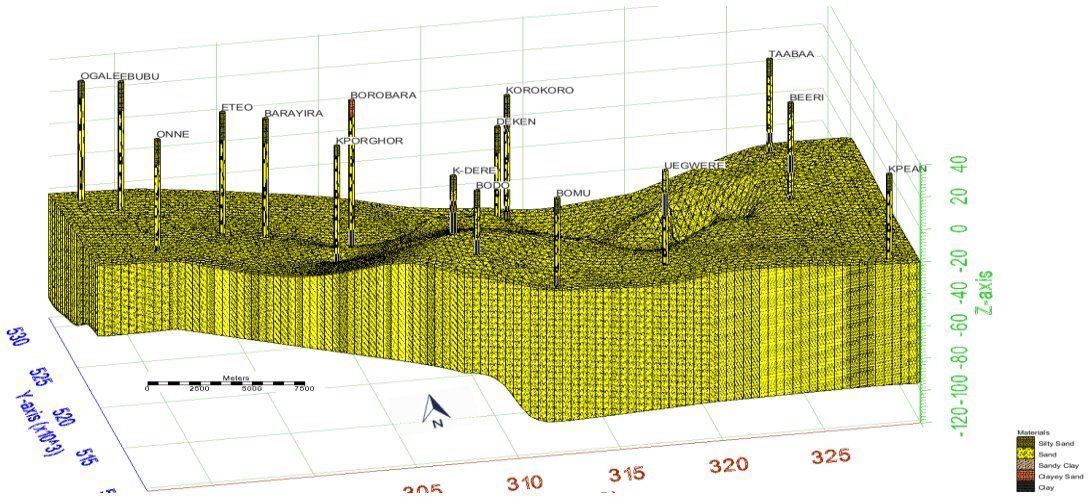


Figure 4.6: Delineation of Deep Aquifer across the study area

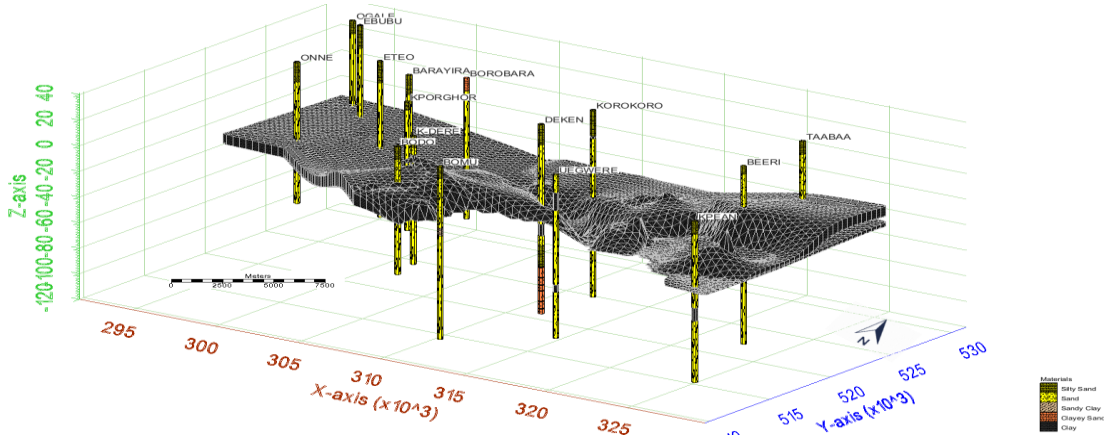


Figure 4.7: Delineation of Clay interbedded layer between upper and deeper aquifer intervals

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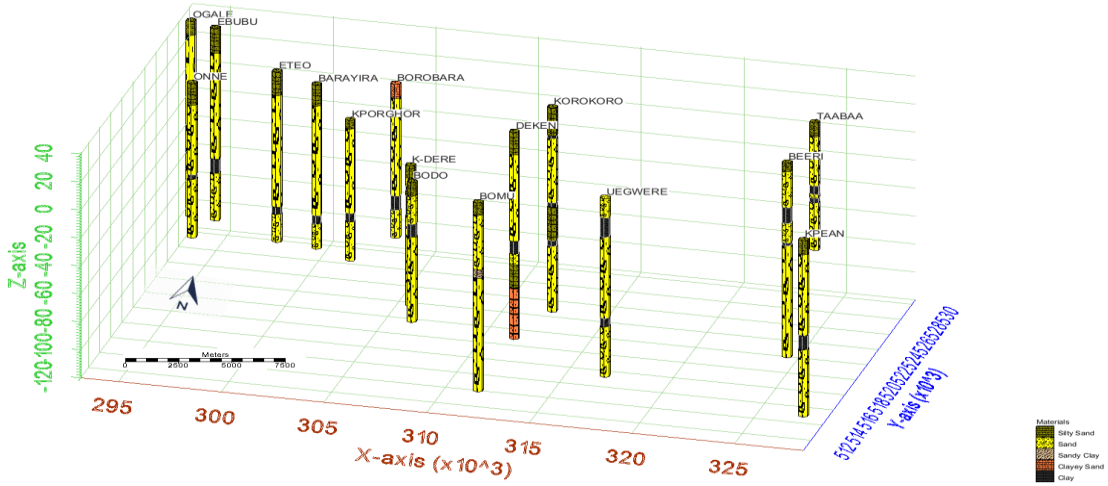


Figure 4.8: Borehole logs showing lithologic types across the study area

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
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						

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Parameter	Unit	Min	Max	Average	S.D	WHO (2006)
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						-
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

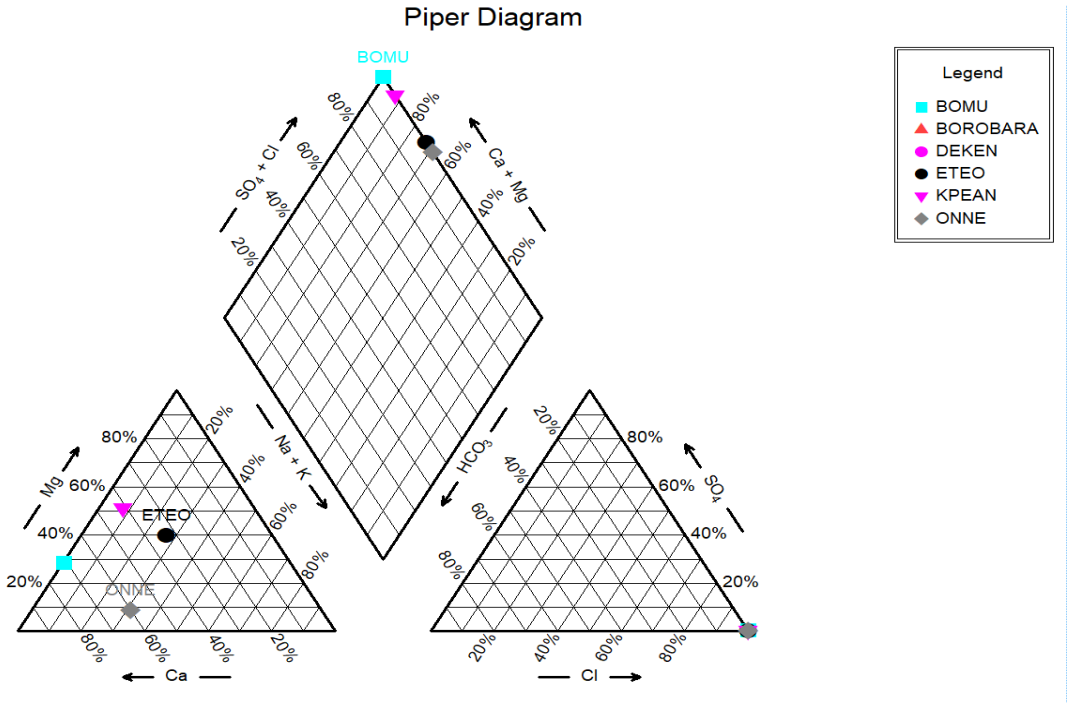


Figure 3.5: Piper diagram showing groundwater hydrogeochemistry for upper aquifer in the study area

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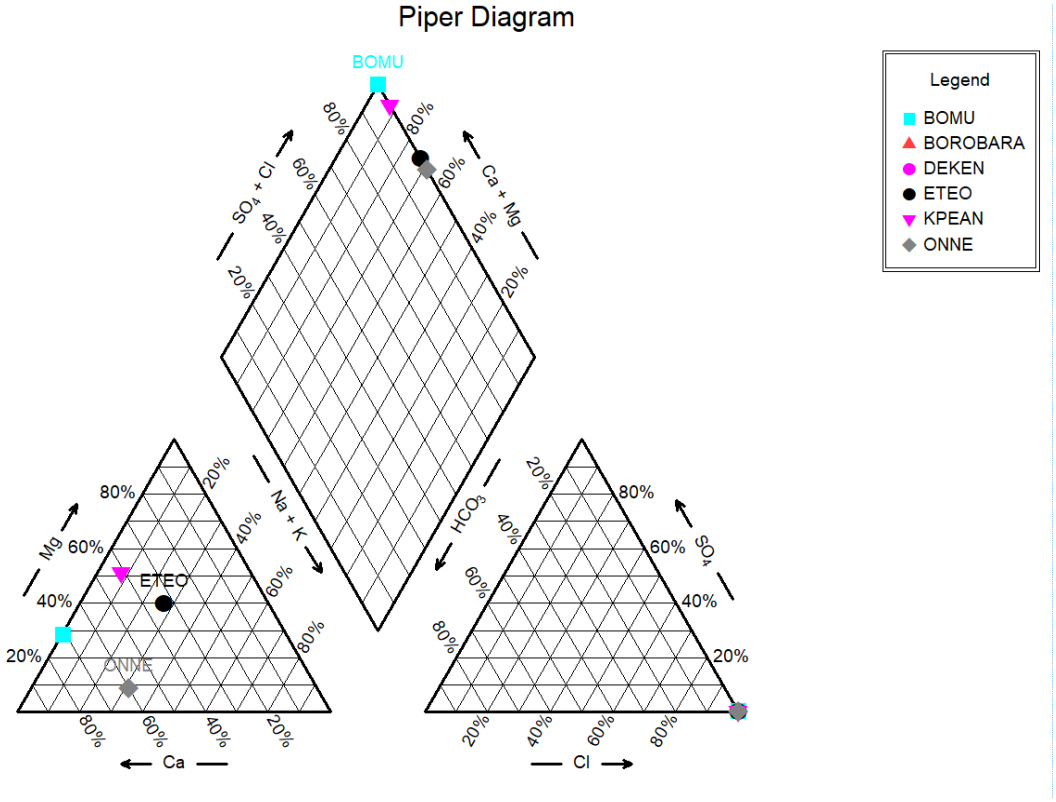


Figure 3.6: Piper diagram showing groundwater hydrogeochemistry for deep aquifer in the study area

Discussion

The findings of this study demonstrate considerable vertical and spatial variability in aquifer characteristics and groundwater quality throughout Ogoniland, indicative of the intricate hydrogeological framework of the Niger Delta. The separation of upper and deep aquifer systems shows that the depth and thickness of these systems vary a lot between the communities that were studied. The shallow aquifers were between 15 m and 80 m thick, and the deep aquifers were between 20 m and 85 m thick. The top of the deep aquifer also changed a lot, going from 16.00 masl in Taaba to more than 109 masl in Ebubu. These differences show that the Benin Formation is not uniform, which is in line with earlier research that says the Niger Delta aquifer system is multilayered, discontinuous, and very variable because of alternating sands and shale intercalations (Etu-Efeotor & Akpokodje, 1990; Akpokodje et al., 1996).

The heterogeneity in aquifer geometry has significant consequences for groundwater presence, flow dynamics, and susceptibility to contamination. K-Dere and Bodo are examples of places where shallow aquifers are thinner. These areas are more likely to

have contaminants get in quickly because they don't have as much natural attenuation capacity. On the other hand, thicker and deeper aquifers, like the ones in Beeri and Bomu, may offer some protection. However, Ogoniland's lack of a continuous confining clay layer makes it more likely that contaminants will move vertically. This finding is consistent with recent research in the Niger Delta, which underscores that the absence of protective aquitards facilitates the vertical migration of hydrocarbons and other contaminants into deeper groundwater systems (UNEP, 2011; Nwankwoala, 2014).

The differences in aquifer depth and thickness across Ogoniland also show how the depositional environments are different. Coastal and transitional zones generally display more intricate stratigraphy, whereas inland regions are characterized by continental sands with greater permeability. Edet et al. (2014) made similar observations, saying that the distribution of sedimentary facies and the interaction between rivers and the sea have a big effect on the properties of aquifers in the Niger Delta. This variability has an effect on the recharge, storage, and quality of groundwater, which in turn affects how well groundwater can be used for home and business purposes.

Also, the difference in depth between shallow and deep aquifers is very important for changes in groundwater quality. Shallow aquifers are more likely to be contaminated from the surface by human activities like oil spills, gas flaring, and waste disposal, which are common in Ogoniland. Deep aquifers are somewhat protected, but they are not completely safe because the aquifer system is connected. Recent research indicates that hydrocarbon contamination, encompassing BTEX compounds, can penetrate considerable depths in the Niger Delta, particularly in regions characterized by high permeability and fractured formations (Li & Zhou, 2011; Nwankwoala, 2014).

The results also indicate that hydrogeochemical processes like dissolution, ion exchange, and redox reactions play a role in the changes in groundwater quality that were seen. Aquifer lithology, residence time, and the interaction between groundwater and host sediments all have an effect on these processes. Recent hydrogeochemical studies have documented analogous processes, emphasizing the influence of natural geochemical reactions in altering groundwater composition in conjunction with anthropogenic inputs (Nourmoradi et al., 2012; Edet et al., 2014).

The differences in aquifer characteristics also affect how groundwater is used and managed. When designing a borehole, such as where to put the screen and how deep to dig, you need to think about the unique characteristics of both shallow and deep aquifers to make sure the water supply is sustainable and the risk of contamination is low. The findings substantiate the necessity for integrated groundwater monitoring systems and site-specific hydrogeological evaluations, as advocated in recent groundwater management research in sub-Saharan Africa (Taylor et al., 2012).

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The study demonstrates that groundwater systems in Ogoniland are highly dynamic and susceptible to both natural and anthropogenic influences. The notable spatial and vertical variations observed highlight the necessity of comprehensive aquifer characterization for comprehending groundwater quality trends and evaluating potential health risks. These results are in line with recent studies done in the area and around the world. They show that we need better ways to protect groundwater, especially in oil-producing areas where environmental pressures are high.

From 6.0 masl in Beeri and Kporghor to 27.83 masl at Uegwere, the Upper Aquifer's top shows substantial geographic fluctuation. Local topographic relief, depositional variations, and shallow stratigraphic heterogeneity factors that have been previously recognized as important influences on the shallow groundwater table in Ogoniland are probably responsible for this variation (Weli et al., 2021; UNEP, 2020). The findings imply that the majority of settlements, which have an average elevation of roughly 13.2 masl, possess a shallow groundwater system that is highly responsive to surface replenishment and susceptible to surface pollution. With an average mean of 52 meters, the thickness of the Upper Aquifer varies greatly, ranging from only 15 meters at K-Dere to 80 meters in Eteo. Units of thick sand like those in Eteo (80 m), Borobara (70 m), and Ebubu (75 m) could be high-energy fluvial facies or paleo-channel deposits, which usually improve aquifer transmissivity and recharge potential (Amadi et al., 2023; Duluora & Nwankwoala, 2022).

With top altitudes ranging from 16.0 masl at Taaba to 109.3 masl in Ebubu, the Deep Aquifer exhibits much more spatial heterogeneity, showing a vertical variation of over 90 m throughout the studied region. This wide range suggests that regional structural elements including growth faults, subsurface channels, and differential compaction geomorphologic processes known to alter the architecture of deep aquifers in the eastern Niger Delta have an impact (Okiwelu & Ozo, 2024; Ehirim & Nwankwoala, 2021). The Deep Aquifer's thickness likewise varies greatly, averaging 47 meters and ranging from 20 meters in Eteo and Barayira to 85 meters in Beeri. While the thinner deep aquifer units at Eteo and Barayira may reflect localized clay intrusion or lower-energy depositional settings, the noticeably thick sections in communities like Beeri (85 m), Kpean (55 m), and K-Dere (65 m) indicate high storage potential and the likelihood of sustained groundwater yield (Amajor et al., 2022; Wokoma & Amadi, 2023).

All things considered, the geographical variation seen in both aquifer levels confirms the widely accepted theory that a complex interaction between sedimentological processes and structural influences shapes Ogoniland's hydrogeology. The region's groundwater availability, vulnerability, and long-term management are significantly impacted by the variation in aquifer depth and thickness.

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There are two main aquifer systems in the research region, according to the subsurface hydrostratigraphy: a shallow or upper aquifer and a deeper aquifer, which are divided by a mostly clayey layer that is laterally discontinuous. The stratigraphic structure is congruent with the hydrogeologic framework of the Benin Formation, where multi-layered aquifer–aquitard complexes typical of the eastern Niger Delta are produced by alternating sand and clay strata (Nwankwoala & Udom, 2020; Ehirim & Nwankwoala, 2021). The intervening clay horizon is a semi-confining unit due to its discontinuous character; dense clay sections limit vertical groundwater flow, but thinner or sandy intervals allow hydraulic contact between aquifers. Similar findings have been documented in Ogoniland and nearby coastal regions, where the aquifer system's partial vertical connection is produced by semi-confining strata (UNEP, 2020; Olobaniyi & Nwankwoala, 2022).

By enabling diffuse recharge, surface runoff, and penetrating rainfall to move downhill through permeable "windows" or weak spots in the clay layer, this partial connectedness increases the possibility for vertical recharge. Research conducted throughout the Niger Delta has shown that these vertical percolation channels play a major role in recharging deep aquifers, especially in regions with high infiltration capacity and sandy interbeds (Amadi et al., 2023; Duluora & Nwankwoala, 2022). As a result, the study area's deeper aquifer is not completely contained; rather, it receives sporadic recharge from the aquifer system above it, particularly during times of heavy precipitation.

Ogoniland's upper and deep aquifer groundwater comparison reveals that, with a few local variations, water from both depths typically exhibits little mineralization and acceptable chemical values. Groundwater samples in the upper aquifer showed low total dissolved solids (TDS) between 3 and 58 mg/L and pH values between 5.66 and 7.05; key ions (Ca, Mg, Na, and Cl) were present in low concentrations, while heavy metals were either undetectable or below recommended levels, with the exception of occasionally increased iron. With Ca up to about 8.24 mg/L, Na up to about 1.02 mg/L, and Mg up to about 1.78 mg/L, the deeper aquifer had equally low heavy-metal levels, with the exception of sporadic iron anomalies. The TDS ranged from 2 to 38 mg/L, and the pH ranged from 5.50 to 7.25. Although total coliform counts varied to a moderate degree, microbiological markers were mostly absent (for example, there were no E. coli or fecal coliforms). Most shallow and deep aquifer samples were rated as "Excellent" by the calculated Water Quality Index (WQI), while a small number of sites most notably one shallow aquifer site and one deep aquifer site showed decreased quality. These findings show that although both aquifers typically provide groundwater that is suitable, there are normally only slight variations in quality with depth, though localized degradation at particular levels needs to be addressed.

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Ongoing oil industry activities in Ogoniland — including spills, pipeline leaks, illegal refining, and inadequate infrastructure maintenance — remain major sources of groundwater contamination, often resulting in petroleum hydrocarbon infiltration into soils and aquifers. A recent multi-site assessment found that many Ogoniland wells contain hydrocarbons at levels far exceeding safe drinking-water standards. (UNEP, 2011; Ikenna & Chukwudozie, 2024). In addition, domestic sewage, improper waste disposal, and agricultural runoff (fertilizers, agro-chemicals) contribute to shallow-aquifer contamination through nitrate or microbial inputs (e.g. nitrate contamination via sewage has been reported elsewhere in Niger Delta groundwater) (e.g. isotopic study of nitrate in eastern Niger Delta aquifers shows sewage-derived contamination) (Aghogho, Egbai & Okolie, 2024). In the present study, although hydrocarbon indicators were mostly below detection, the modest total coliform presence in shallow wells suggests infiltration of surface-derived microbial contaminants. Given the semi-confined nature of the aquifer system and lateral discontinuity of the clay confining layer, such contaminants may percolate from the surface into the upper aquifer, and through permeable windows eventually migrate downward — meaning that contamination sources at the surface can have depth-dependent impacts.

The hydrostratigraphic configuration identified in this study—comprising a shallow (upper) aquifer and a deeper aquifer separated by a laterally discontinuous clay layer—confirms the complex, multi-layered nature of groundwater systems in the Niger Delta. Recent studies have similarly characterized the region as comprising interbedded sands and clays within the Benin Formation, resulting in semi-confined to unconfined aquifer systems exhibiting varying degrees of hydraulic connectivity (Abam & Nwankwoala, 2020; Tanko et al., 2024). The discontinuity of the clay layer observed in this study is particularly significant, as it facilitates vertical leakage and interaction between aquifer units, a characteristic commonly documented in coastal sedimentary basins.

The semi-confining clay horizon serves as a protective barrier and a pathway for groundwater flow. It limits vertical movement when it is continuous, but when it thins or becomes sandy, it makes preferred pathways (permeable windows) for recharge and contaminant movement. Recent hydrogeological studies have highlighted this dual role, demonstrating that such discontinuities facilitate vertical recharge while simultaneously heightening aquifer vulnerability, especially in oil-producing areas characterized by significant surface contamination (Gbadebo et al., 2026; Oluwadare & Eyinade, 2025). This means that in Ogoniland, deeper aquifers can get water through these windows, but they are not completely safe from pollutants like hydrocarbons and industrial chemicals.

The aquifers' different hydraulic behaviors can also be explained by their different lithologies. The upper aquifer is mostly made up of fine to silty sands. It has a high porosity but a moderate permeability, which means it can easily take in water during the rainy

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season and is more likely to become contaminated. The deeper aquifer, on the other hand, is made up of medium to coarse-grained sands. It has higher permeability and transmissivity, which means it can hold more water and give more reliable yields. Recent hydrochemical and aquifer characterization studies in southern Nigeria have reported similar findings, indicating that coarse-grained sediments correlate with increased transmissivity and enhanced groundwater productivity (Apuyor et al., 2024).

The hydraulic parameters in Table 4.2 show that both aquifer systems are not the same. The upper aquifer has a wide range of hydraulic conductivity values (15.31–264 m/day) because the texture and compaction of the sediment vary. The high transmissivity values seen in places like Bomu show where there is a lot of groundwater potential. On the other hand, lower values in places like Eteo point to limited flow conditions. This spatial variability aligns with recent research that underscores the impact of depositional environments and sediment heterogeneity on aquifer performance in coastal Nigeria (Hassan et al., 2019; Tanko et al., 2024).

The deep aquifer also has a wide range of hydraulic conductivity and transmissivity values, which means that there are both high-yield and low-yield zones. Even though it is deeper and has a coarser composition, the deep aquifer still shows semi-confined conditions, as shown by storativity values between 10^{-4} and 10^{-7}. This confirms that the aquifer is not completely closed off and is still connected to the upper system through water flow. Recent studies in the coastal aquifers of the Niger Delta indicate comparable semi-confined conditions, where groundwater flow is affected by both vertical leakage and lateral movement within permeable sand units (Aghogho et al., 2024).

The proximity of hydraulic heads and static water levels between the upper and deep aquifers further substantiates the presence of vertical hydraulic interaction. This means that groundwater could flow between the two systems, depending on how the pressure changes in the area. This kind of connectivity has a big effect on the quality of groundwater because pollutants that get into the surface or the shallow aquifer can move down over time. Recent hydrogeochemical studies in the Niger Delta have documented analogous trends, revealing contamination signatures across various aquifer depths attributable to vertical connectivity (Gbadebo et al., 2026).

The results show that the aquifer system in Ogoniland is different in some ways, not completely closed off, and connected by water. The deeper aquifer gives a higher yield and some protection, while the discontinuous clay layer is both a way for water to get in and a place where it is more likely to get damaged. This duality highlights the necessity for meticulous groundwater management, encompassing the safeguarding of recharge zones, regulation of surface activities, and ongoing monitoring of groundwater quality. The results are in line with recent research that says that sustainable groundwater

development in the Niger Delta needs to consider both the area's hydro stratigraphic complexity and the growing pressures from people.

The Piper diagram interpretation provides important insight into the hydro chemical evolution and controlling processes of groundwater within both the shallow and deep aquifers in Ogoniland. The dominance of the calcium–chloride (Ca–Cl) water type across both aquifer systems indicates a strong influence of salinity and marine-related processes on groundwater chemistry. 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 facies is widely reported in coastal aquifer systems and is often associated with saline water intrusion, ion exchange processes, and water–rock interaction (Adimalla & Qian, 2019; Ukah et al., 2020).

The prevalence of Ca–Cl type water in both shallow and deep aquifers suggests that the groundwater system is influenced by a combination of geogenic and marine processes. In coastal environments such as the Niger Delta, chloride enrichment is commonly linked to seawater intrusion or the presence of connate (fossil) marine water trapped within sedimentary formations. Recent studies in the Niger Delta have similarly reported chloride-dominated hydrochemical facies as evidence of saline intrusion and tidal influence, particularly in areas close to estuaries and tidal rivers (Ukah et al., 2020; Egbueri & Unigwe, 2020). The higher chloride dominance observed in southern locations such as Bodo and Onne compared to northern areas like Beeri and Uegwere further supports this interpretation, indicating a clear salinity gradient toward the coastal zones near the Bonny River.

In addition to marine influence, the elevated calcium concentrations observed in the groundwater may result from geochemical processes such as the dissolution of calcareous materials and cation exchange reactions. In clay-rich environments, sodium adsorbed on clay minerals can be exchanged with calcium in groundwater, leading to calcium enrichment and the development of Ca–Cl type water. This process has been widely documented in sedimentary basins where groundwater interacts with clay and shale layers (Subba Rao et al., 2017; Adimalla & Qian, 2019). The presence of a discontinuous clay layer separating the upper and deep aquifers in Ogoniland likely facilitates such ion exchange processes while also allowing limited vertical mixing.

The hydrostratigraphic setting further explains the observed hydrochemical patterns. The semi-confining clay layer, though discontinuous, permits hydraulic connectivity between the shallow and deep aquifers. This allows for partial vertical mixing of groundwater, enabling the transfer of dissolved ions between aquifer units. Consequently, both aquifers exhibit similar hydrochemical signatures despite differences in depth. Recent hydrogeochemical studies emphasize that such semi-confined systems often display

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overlapping water types due to leakage and recharge through permeable zones (Egbueri et al., 2021). This is particularly relevant in Ogoniland, where the absence of a continuous confining layer enhances both recharge and contaminant migration.

The physicochemical data presented in Table 4.7 further support the Piper diagram interpretation. The relatively low to moderate concentrations of calcium (0.056–4.261 mg/L) and magnesium (0.032–1.023 mg/L) indicate limited mineralization, while the variability in chloride concentrations (0.05–9.77 mg/L) reflects localized salinity influences. Electrical conductivity (7–116 µS/cm) and total dissolved solids (3–58 mg/L) are generally low, suggesting that the groundwater is fresh but beginning to show signs of chemical evolution in certain areas, particularly those closer to the coast. Similar trends of low TDS but increasing chloride content have been reported in recent studies of coastal aquifers undergoing early-stage salinization (Egbueri & Unigwe, 2020).

The slightly acidic to neutral pH range (5.66–7.05) observed across the study area may be attributed to the influence of organic matter decomposition and carbon dioxide dissolution, which can lower pH in shallow aquifers. Elevated iron concentrations, particularly the high value recorded at Onne (1.026 mg/L), may be linked to reducing conditions and the dissolution of iron-bearing minerals, a common feature in deltaic environments (Ukah et al., 2020). The consistently low nitrate levels (<0.001 mg/L) across all locations suggest minimal impact from agricultural activities or sewage contamination, indicating that anthropogenic nutrient pollution is currently limited in the study area.

Overall, the hydrochemical characteristics indicate that groundwater in Ogoniland is primarily controlled by natural geochemical processes, including mineral dissolution, ion exchange, and residual marine influence, with limited but significant contributions from vertical mixing between aquifers. The dominance of Ca–Cl facies, particularly in deeper aquifers, highlights the vulnerability of the groundwater system to saline intrusion and underscores the influence of the coastal hydrogeological setting. These findings are consistent with recent hydrogeochemical studies in coastal Nigeria and other deltaic environments, which emphasize the combined role of geology, hydrodynamics, and marine processes in shaping groundwater chemistry.

Conclusion

This study has shown that the Ogoniland aquifer system is very different from one another, has different layers, and is connected by water flow. This is because the Niger Delta has a very complicated hydrogeological structure. The separation of upper and deep aquifers showed that their depth, thickness, and hydraulic properties varied a lot from one place to another. This confirms that the Benin Formation is made up of multilayered, discontinuous sedimentary units that alternate between sands and clays. The shallow aquifer, which is 15 to 80 meters thick, is usually more responsive to recharge but is also

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very easy to contaminate from the surface. The deeper aquifer, which is 20 to 85 meters thick, has a higher storage capacity and groundwater yield, but it is also easy to contaminate because it does not have a continuous confining layer.

A semi-confined system with partial hydraulic connectivity is created by a clay horizon that is not continuous between the aquifers. This structural feature serves a dual purpose: it allows for vertical recharge through permeable windows, but it also makes it more likely that contaminants will move between aquifer units. Because of this, groundwater in both shallow and deep systems shows signs of interaction, with similar hydrochemical signatures seen at different depths. The hydraulic parameters further confirm that the aquifers are not all the same. They show areas with high transmissivity and groundwater potential as well as areas with limited flow conditions.

Hydrochemical analysis, including the interpretation of Piper diagrams, shows that the groundwater in the study area is mostly of the calcium-chloride (Ca–Cl) type. This is because of a combination of geogenic processes, ion exchange, and leftover marine inputs. The growing presence of chloride in coastal areas like Bodo and Onne may be due to saline intrusion and tidal processes that happen near the Bonny River. Most of the groundwater samples, on the other hand, had low total dissolved solids and physicochemical properties that were generally acceptable. This means that the groundwater is mostly fresh and safe to use. Localized anomalies, such as increased iron concentrations and moderate microbial presence in certain shallow wells, indicate site-specific contamination risks.

Human activities, especially oil exploration, spills, illegal refining, and bad waste management, are still big threats to the quality of groundwater in Ogoniland. Because the aquifer system is only partially confined, pollutants that get into the surface can get into shallow aquifers and, over time, move to deeper areas. Even though the hydrocarbon indicators were mostly low in this study, the hydrogeological conditions suggest that the area is very likely to become contaminated in the future if protective measures are not taken.

The study shows that the quality of groundwater in Ogoniland is affected by a mix of natural geochemical processes, hydrostratigraphic complexity, and human activities. The general quality of the water is good and is considered excellent in most places. However, the observed vertical connectivity and spatial variability show that proactive groundwater management is needed. To use groundwater resources in the region in a way that is good for the environment, boreholes must be designed for each site, recharge zones must be protected, contaminant sources must be controlled, and both shallow and deep aquifers must be monitored all the time. These steps are necessary to protect groundwater resources and lower the risk of health problems in this area, which is both environmentally sensitive and important to the economy.

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