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RESEARCH ARTICLE

Groundwater quality assessment around Lake Mkpitime, Nigeria, using integrated geophysical and hydrochemical approaches

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ABSTRACT

Groundwater quality assessment around Lake Mkpitime has not received any investigations. The goal of this study was to apply integrated geophysical and hydrochemical approaches to investigate the suitability of the groundwater around the lake for domestic, agricultural and industrial sustainable use. Ten vertical electrical soundings (VES) were conducted within the lake vicinity, while four groundwater samples and seven lake samples were collected for water quality assessment. The VES result revealed an aquifer depth range of 14.8 – 108 m, located within the fourth layer, while the aquifer resistivity ranged from 645 – 5287 Ωm. Dar-Zarrouk parameters evaluation revealed values of longitudinal conductance (0.03-0.213 Ω^{-1}), transmissivity (1.94-98.62 m^2/day), transverse resistance (47247-313525 Ωm^2), indicating an aquifer with poor to intermediate protective capacity and low to intermediate potential. The hydrochemical analysis of groundwater samples revealed dominant calcium (Ca^{2+}) – sodium (Na^+) – bicarbonate (HCO_3^-) – chloride (Cl^-)- sulphate(SO_4^{2-})water facies, while the lake samples revealed Ca^{2+} - Na^+ - HCO_3^- Cl^- - SO_4^{2-} water facies, indicating water mixing and suggestive of lake and groundwater interaction, as groundwater close to the lake has higher concentrations and possible stratification of water chemistry with depth. The fresh water nature of groundwater was revealed by the maximum TDS range of 10.8-19.3 mg/l, while that of the lake ranged from 10.8-31.3 mg/l, implying fresh-moderate subsurface mineralization, with groundwater that is within the permissible limit of the World Health Organization. The results showed that the groundwater quality around the lake is suitable and sustainable for both domestic, agricultural and industrial needs.

INTRODUCTION

Globally, human civilization has prospered tremendously around water sources, especially in the vicinity of river banks and lakes (Kotra et al., 2016). However, this progressive development around the coastal areas has caused groundwater suffer greatly in its ability to maintain its basic characteristics due to indiscriminate exploitation. Development projects require a sustainable supply of freshwater, but the absence of nearby surface water resources, makes groundwater resources demand, the alternative (Eltarabily and Negm, 2019; Ohwoghere-Asuma et al., 2020; Ismail et al., 2023). Groundwater accounts for about 98 % of the world's water needs. It becomes an obvious choice for sustainable supply for freshwater for developmental projects, due to the fact that it is not easily affected by natural conditions or contaminants from the surface. The sole reason for this being that the earth's layers act as natural filter for contaminants (Iserhien-Emekeme et al., 2020; Chinyem et al., 2023; Chinyem, 2024). Thus, the search for groundwater becomes a viable choice for sustainability in terms of its quality and quantity for domestic, agricultural or industrial use. Groundwater assessments involve multiple approaches, depending on the kind of interpretation that will help achieve the management strategies. Therefore, a proper knowledge of the qualitative and quantitative changes in groundwater system becomes crucial for its effective management.

Generally, groundwater quality assessments have been carried out in different geologic terrains of the world, using various geophysical, hydrogeochemical and geological approaches. Electrical and hydrogeochemical methods have been employed widely in hydrogeological investigation in coastal areas (Zarroca et al., 2011). The electrical method, employing the electrical resistivity technique, has been widely utilized technique in the investigation of groundwater resources because of its excellent performance and its sensitivity to delineate conductive anomalies, cost effectiveness, as well as quality of data (Chinyem, 2013; Chinyem, 2017; Himi et al., 2017; Abdelfattah et al., 2021; Gamal et al., 2023).

Detailed knowledge of groundwater quality is critical as it affect the numerous applications of water. It therefore, becomes necessary to define the quality of groundwater, as well as characterize its hydrogeochemical status with a view to assessing its suitability for various purpose.

Issele-Mkpitime area is one of Nigeria's coastal regions, located northeast (NE) of the western Niger Delta (Ofomola et al. 2016; Bawallah et al. 2021). Increase in human demands for potable water, in addition to the expansion of national projects around the area have necessitated the urgent need for long term water supplies in the area. Just like most communities in the Niger Delta, the area has suffered from poor and inadequate access to potable water for domestic and agricultural purposes. This is attributed to groundwater quality deterioration, basically from shallow boreholes (Ohwoghere-Asuma et al. 2020). Ohwoghere-Asuma et al. (2020) reported a slightly acidic (5.6-7.4) groundwater(aquifer) in a coastal aquifer of Oporoza-Gbaramatu, in Niger Delta, as well as high concentrations of dissolved ions. Their results for some major cations revealed values for sodium, Na^+ (30.72-120.8 mg/l), potassium, K^+ (8.72-23.72 mg/l), magnesium, Mg^+ (12.76-23.95 mg/l) and calcium, Ca^{2+} (17.5-39.88 mg/l), while the results for anions indicated (chlorides) Cl^- (43.45- 243 mg/l), bicarbonates HCO_3^- (58.44-99.8 mg/l), sulphates SO_4^{2-} (60.42-165.15 mg/l), and phosphates NO_3^- (0.4 -34.22 mg/l). Thus, valuable resources such as lake resources, become polluted by land and water-based societal activities, leading to the contamination of the nearby aquifers. Furthermore, Lake Mkpitime, the only surface water resource in the area is influenced by seasonal rainfall. The increase in water demand in Issele-Mkpitime area, was acknowledged during the last two decades as a result of the establishment of natural agricultural development projects in the region. More than 80% of the water to be used in the projects will be sourced from nearby freshwater resources. Noted that the use of contaminated surface water resources (lake) for domestic and agricultural needs portends several health challenges, this study was undertaken as a contribution to the investigation for additional better long term quality water supply in the area. Several research and donor agencies (e.g. European Union, United Nation's Children Emergency Fund, Niger Delta Development Commission) in collaboration with the government of Delta State have been actively involved in several communities of the state, with a view to ameliorating the impending water supply challenges in the communities (Akpan et al. 2013; Ebong et al. 2016; Chinyem et al. 2024). Several concerted efforts, geared towards tackling these challenges have been made by these agencies through funding of water well drilling in communities, and provision of social amenities in order to alleviate their sufferings. It becomes imperative therefore, that groundwater resources, to be suitable for the above-mentioned purpose, requires routine assessment in order to evaluate its quality (Ebong et al., 2016). Several studies have been carried out on groundwater quality assessments and hydrochemical characterization in various regions of the world (Ebong et al., 2016; Song et al., 2020; Rehman et al., 2020; Gamal et al., 2023; Musa et al., 2023). Ebong et al. (2023) applied geoelectrical and geochemical approaches to assess the groundwater quality in Abi area, Southeastern Nigeria. Their findings revealed that the water quality was influenced by several geologic processes. However, the water quality was classified to be good to excellent, which was an indication of its suitability for both domestic and agricultural purposes. Song et al. (2020) employed integrated geophysical and hydrochemical approaches to the protection of groundwater in the Upper Gu Song River recharge area, Sichuan Basin, China for its suitability for drinking purposes. Their findings revealed that the risk zone for the drinking water source covered an area of 33.9 km^2, which accounted for about 35 % of the study area. Their research findings were able to provide scientific basis for the identification of groundwater for drinking in Karst regions and also to provide a decision-making for the protection of drinking water in Karst regions. Rehman et al. (2020) also used integrated geophysical and hydrogeologic techniques to investigate groundwater contamination in Wadi Bani Malik dam area, Jeddah, Saudi Arabia. Their reports showed that the values of the total dissolved solid (TDS) were significantly higher in the upstream region of the dam than the downstream region, suggestive of the source of contamination from the upstream reservoir source. The integrated study indicated that the groundwater is not suitable for both drinking and irrigation needs. In addition, Gamal et al. (2023) used integrated geophysical and hydrochemical approaches to assess the groundwater quality along West of New Damietta Coastal City, Egypt. The geophysical result identified five geoelectric layers with resistivity that ranged from 1-9 Ωm and aquifer thickness that ranged from 29-42 m, located at 65 to 70 m depths. The identified aquifer comprised sands, gravel with clay intercalation. The hydrochemical result showed an aquifer dominated by Na-Cl water facies, and the total dissolved solids (TDS) range of 7035 – 7735 mg/l, revealed a brackish nature of water for the power plant's sustainable use. Musa et al. (2023) equally applied integrated geoelectrical and borehole data to characterize basement rock aquifers of Lokoja, Nigeria. The study revealed an aquifer range of 60-90 m, with transmissivity and hydraulic conductivity values of 2.058-1761.033 m^2/day and

0.205-138.664 m/day, respectively, indicating high porosity and permeability in the southern part of the study area. The aquifer characteristics showed a moderate to good groundwater prospects, thus the integrated approaches applied in the area, could solve challenges of perennial low yield and abortive boreholes in the study area and environs.

Similarly, many scholars have used integrated geophysical and hydrochemical approaches to assess groundwater resources in terms of its quality (Das and Dhiman, 2003; Rao, 2003; Chandra et al., 2006; Inoubli et al., 2006; Milovanovic, 2007; Gemail et al., 2011; Akpan et al., 2013; Kotra et al., 2016; Salem et al., 2019; Ding et al., 2020; Hengazy et al., 2020; El-Kholy et al., 2022; Ismail et al., 2023). Their reports showed that groundwater suitability for drinking and irrigation could be assessed by applying integrated study.

Specifically, Ofomola et al. (2016) used combined geophysical approaches (magnetic susceptibility and electrical resistivity) at Issele-Mkpitime lake area, with a view to "delineating weak zones that could act as migrating pathways for groundwater recharge to the lake". Their findings revealed the presence of fractures/weak zones that are structurally, controlled and could lead to the recharge of the lake. Furthermore, Bawallah et al. (2021) investigation in the study area only focused on "the application of integrated geophysical study in order to evaluate geologic factors that are responsible for foundation stability and vulnerability to failure Issele-Mkpitime area. The research findings revealed that the area is highly vulnerable to failure due to the weak subsurface materials in the area.

In the research area, Lake Mkpitime, which is a fresh water lake is one of the geomorphic units. The lake is a unique home for both aquatic, terrestrial resource as well as considerable resident and migratory birds' species that can contribute to food security, employment, geo-tourism, geo-heritage and general well-being of the local communities as well as the nation in general. Inspite of its importance, Lake Mkpitime and associated researches about the lake is the least studied of all the Nigerian lakes due to its remoteness, scarcity of trained personnel in geosciences and aquatic sciences. In addition, lack of monitoring, education and training, data and information exchange, have led to insufficient knowledge that will help to better manage the lake. Fundamentally, no information about groundwater quality assessment around Lake Mkpitime has been reported by any researcher. Thus, this study becomes crucial in order to bridge that gap. The goal of this study, therefore, was to assess the groundwater quality around Lake Mkpitime, Southern Nigeria, with a view to determining its suitability for domestic, agricultural and industrial sustainable use. This present study is a novel as there has not been any record pertaining to this aspect of research in the area.

THE STUDY AREA

2.1. Location and geology of the study area

The study area is located in the NE of the Niger Delta Basin (NDB). It is bounded by latitudes 6^{o} 20' and 6^{o} 22.5' N and longitudes 6^{o} 31' and 6^{o} 36' E (Figure 1). It covers an area of 3 km^2 and can be accessed through Mkpitime road, Onicha Olona road, and Atuma road respectively. Topographically, the area is generally of low relief with elevation of 66-289 m above sea level. The area is phased with two climatic seasons: wet and dry seasons. The climate lies within the humid tropical rainforest belt of Nigeria with an average rainfall of about 1500-2000 mm/year. The wet season spans from April-October, while the dry season spans from November- March. The mean annual atmospheric pressure is about 1017 $\pm$ 1.1m bars. The vegetation, typically of lowland rain forest, is characterized by thick forest with trees of different species, shrubs, herbs and ferns. The soil is essentially red to reddish brown loamy sand/soil. In the adjoining villages, streams and springs identified, have their sources from rocks overlain by claystones and interbedded with sandstones in some localities, like Ngene stream, Iyi-Ocha, Adugbe Stream, and the drainage pattern is basically dentritic. Ofomola et al. (2016) reported that "Lake Mkpitime is believed to be filled with water during the wet season and get reduced in volume, during the dry season, hence considered a mystery pool". The Lake Mkpitime and the Coastal Plain sands are the main geomorphic features that characterize the surface of the study area.

Geologically, the area (Lake Mkpitime area) is underlain by coastal plain deposits. These deposits consist of continental sand with lenses of clay and lignite deposited from Eocene to Recent. The study area is within regions where the Niger Delta (ND) lithofacies gradually grades into the Anambra Basin lithofacies. The area is from the surface, underlain by the Benin Formation (BF), representing the main groundwater-bearing unit, followed by the Ogwashi-Asaba Formation (OAF), otherwise known as the Lignite Series, and then the Ameki Formation. The OAF is the lateral equivalent of the upper sequence of Agbada Formation (AgF) of the NDB (Figure 2). Figure 2 shows the NDB stratigraphy as well as nature (diachronous) of the sediments. The NDB geology has been described by many authors (Short and Stauble, 1967; Avbovbo, 1978; Doust and Omatsola, 1990; Etu-Efeotor and Odigi, 1983; Etu-Efeotor and Akpokodje, 1990; Chinyem, 2024). Basically, the basin consists of three diachronous units, namely, the Benin, Agbada and Akata Formations, respectively. The BF (Oligocene-Recent) overlies the AgF, while the latter overlies the Akata Formation (AkF), which is of Palaeocene age. The BF (consists of sands, clay, silt and gravel) is the main groundwater bearing unit that is of great interest to the hydrogeologist (Chinyem, 2024), while the AgF is the principal reservoir rock for petroleum and consists of sandstones and shale, while the AkF, consists of Shales, which are Petroleum source rocks.

Structurally, the NDB is believed to be formed due to the failed rift (aulacogen) of the triple junction system, during the Jurassic, and was subsequently filled with sediments. The rifting, which led to the separation of the African, South American and South Atlantic plates, respectively ended during the mid-Cretaceous, led to the deposition of sands and shales during the late Cretaceous times.

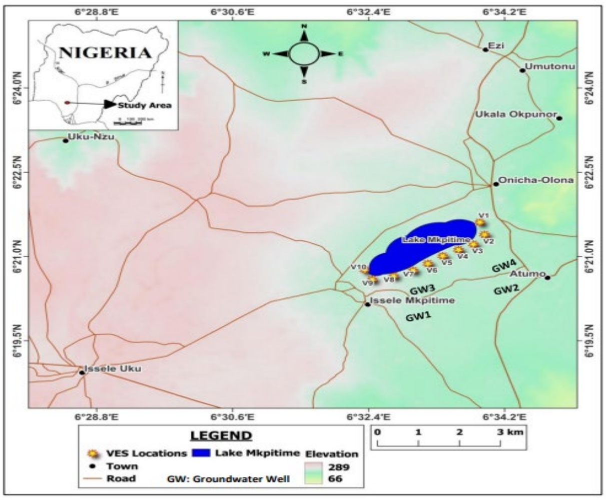

Figure 1: Location map of Issele-Mkpitime area

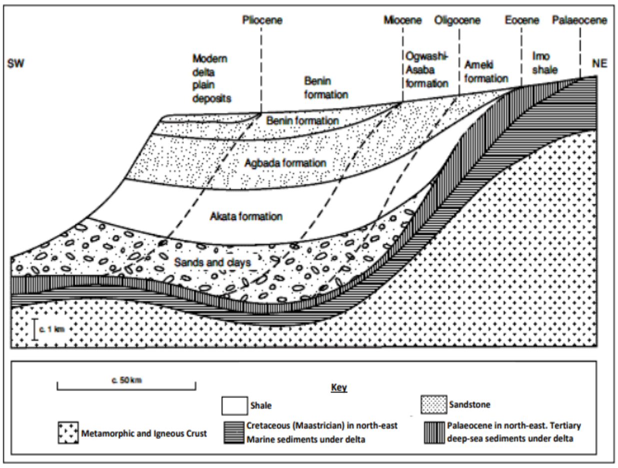

Figure 2: Simplified schematic cross section of the Niger Delta Basin stratigraphy (after Wright et al., 1985)

Hydrogeologically, the sands and clay lenses of the BF (Coastal Plain Sands), constitute the main aquifer units in the area. Etu-Efeotor and Akpokodje (1990) reported that "the aquifer system is non uniform, variable and discontinuous, with thickness of over 120-300 m". Additionally, the authors noted that "there exists a well-defined aquifer that ranged from confined at depth, to semi-confined to confined at the surface, with high degree of variability of static water level from one locality to another". In the basin groundwater recharge is primarily from rainfall (Etu-Efeotor and Akpokodje, 1990).

MATERIALS AND METHODS

Integrated approaches between geophysical method and hydrochemical analysis were utilized in this research to assess the groundwater quality around Lake Mkpitime.

3.1 Geophysical method

The electrical resistivity technique, employing the VES, was used around the lake, because of its excellent performance, ability to identify water bearing layers, its sensitivity to delineate conductive anomalies, cost effectiveness, as well as quality of data obtained (Chinyem, 2017; Abdelfattah, 2021; Gamal et al., 2023). Ten VES data were acquired around the lake, using SAS 1000 Terrameter with the goal to determine the subsurface lithology, water-bearing layers and groundwater quality around the vicinity of the lake. The Schlumberger array was utilized with an electrode spacing (AB/2) that varied between 1 to 300-500 m, depending on field condition. Ward (1990) and Chinyem (2013) reported that "The Schlumberger array is the best method for VES as it is less labour intensive, provides high signal to noise ratios, good resolution to horizontal layers and good depth sensitivity''.

The field data were converted to apparent resistivity value (**ρa**) and the results were plotted against the electrode spacing (current) so as to generate the geoelectric curve required. The obtained data was processed, using Win Resist software, which provided the true resistivity as well as the depth from the apparent resistivity, data observed at each VES location. Geoelectric sections were later constructed from the information obtained from the sounding curves. Lithological evaluation was done, using information from drilled borehole around the area, subsequently, inferences were made on the lithologies that tallied with the geoelectric section. The aquifer hydraulic parameters were equally determined, using the Dar-Zarrouk parameters. Zohdy (1974) and Chinyem (2024) noted that "these parameters are important for the analysis and understanding of geologic model through the integration of resistivity and thickness of the layers". The parameters (longitudinal conductance S, and transverse R) were employed respectively to determine some aquifer parameters, from the relation given by Patra and Nath (1991) as:

Longitudinal resistance (S) = $h/\rho = h \times \sigma$ --------- (1)

Transverse resistance R = $h \times \rho$ --------- (2)

Where h, ρ and σ are respectively, the thickness(m) resistivity (Ω-m) and the electrical conductivity (Ωm^{-1}) of the **ith** layer, obtained from the VES survey. The analytical relationship between the Dar-Zarrouk parameters and the transmissivity can obtain, according to Niwas and Singhal (1981) as:

$T = K \sigma R$ ------- (3)

$T = KS / \sigma$ ------- (4)

Where **T** is the transmissivity (m^2/day), **K** is the hydraulic conductivity (m/day), **R** is the transverse resistance of the aquifer (Ωm^2), **S** is the longitudinal conductance (Ω^{-1}) and **σ** is the electrical conductivity (Ωm^{-1})

However, due to lack of information of **K** from some existing boreholes in the area, the K used in this study was determined from the relationship according to Heigold et al. (1979), and used by Obiora et al. (2016); Raji and Abdulkadir (2020); Seli et al. (2021); and Musa et al. (2023) as follows:

$K = 386.40\rho^{-0.93283}$ ……… (5)

Where K = hydraulic conductivity (m/day)

ρ = aquifer resistivity (Ωm)

Furthermore, Niwas and Singhal (1981) established that "in areas of similar geologic settings and water quality, a constant could be valid for such area under investigation". Thus, the computation of K and T, respectively, for the entire area were estimated using the relationship in equation (5), and this aided the determination of the aquifer hydraulic parameters, utilized in this research.

3.2 Hydrochemical analysis

Seven (7) surface water (SW) samples were taken randomly from the lake, the depth of which were at least 30-40 cm. The bottle (sterile 500 ml plastic bottle) for sample collection was rinsed thoroughly with the sample water to remove any possible contaminant and labelled with a permanent marker, according to the sample location. The 500 ml bottle was later immersed in the lake, filled and covered with cap and then placed in a cooler. Four (4) groundwater (GW) samples were also taken from four producing groundwater wells within the study area, in order to correlate with the SW samples. The GW samples were taken after ten minutes pumping in order to attain stable chemical conditions. In the same vein, the GW samples were taken with 500 ml sterile plastics bottle, filled during pumping, sealed and labelled accordingly. Physical parameters were measured in the field using conductivity meter (SKU 305130-PEN). The portable meter is an advanced, multipurpose, high-performance, quick and accurate pen-type instrument that was electrical conductivity (EC) total dissolved solid (TDS), PH, etc. The selected seven sampling points for SW and four GW, were sampled once during the dry season (November 2023) and wet season (July 2024) respectively. The samples collection, storage and monitoring were done strictly according to the relevant American Public Health Association (APHA, 2005) standards. The location coordinates (geographic) of the water sampling (SW and GW respectively) and the VES locations, employed in posting the locations on the map were done, using GPS Map 76C global positioning system model. Analysis of the water samples (SW and GW) were carried out in the Advanced Research Laboratory Limited, Delta State University, Abraka, Nigeria, with the atomic absorption instrument (AAS) according to the American Public Health Association (APHA, 2005). The concentration values of all the water samples were expressed in milligram per litre (mg/l), and the results of the water analysis were used to identify, as well as evaluate the water type in the study area through the use of Piper diagram.

3.3 Hydrochemical Statistical Analysis

Statistical analysis was carried out on the generated concentration values of some parameters analyzed, and bar charts were used to represent the concentrations of some parameters across the sample locations. Linear direction (rise/fall) of the concentrations of the SW and GW were estimated and correlated with Microsoft excel, while the piper diagrams were constructed with grapher software.

RESULT AND DISCUSSION

4.1 Geophysical assessment

Ten VES points were occupied, and the results of the geoelectric interpretation are presented in Table 1. The interpretation of VES curves shows the presence of low resistivity with depth, and this could be attributed to the presence of clay/clayey sand, fine/silty sand. The variations in resistivity with depth might be caused by changes in grain sizes of deposit, water saturation ratio as well as clay interference limit. Moreso, the closeness of the VES points to the lake will cause both lateral and vertical resistivity levels reduction, and due to the predominance on permeable lithologic section, lake water intrusion is possible, especially at a low topographic area. Thus, water chemistry as well as its quality at such geological setting becomes extremely affected.

The geoelectric parameters, obtained from the VES data interpretation (Table 1) reveals five geoelectric layers. The uppermost geoelectric layer (first geoelectric layer) has a regular expansion and is primarily made up of top soil with a thickness range of 0.2-1.7 m, depth range of 0.2-1.7 m and resistivity of 208.7-1564 Ωm. the underlying layer (second geoelectric layer) is composed of mostly fine, medium-coarse sand with a thickness range of 0.9-9.3 m, depth range of 2.2-10.7 m and a resistivity of 448.9-5249.2 Ωm. the third geoelectric layer, corresponds to clay sediments, clayey sand, fine to medium sand. This layer displays finer facies with resistivity of 33-725.5 Ωm, thicker layer than the previous layers (3.4-15.6 m), depth range of 11-25.5m. the fourth layer is composed of medium to coarse sand, with resistivity value of 654.1-5287.1 Ωm thickest of all the layers (14.5-108 m) and a depth range of 29.4-122.2 m. This later represents the main aquiferous layer (water-bearing unit). The lowermost geoelectric layer (clay, clayey-coarse sand) displays resistivity range of 676-927.2 Ωm, reflecting clayey, to coarse sand, with fresh water conditions. This is also identified as a continuation aquifer, through the exact thickness as well as depth could not be ascertained, because the current electrode separation terminated within the zone.

Table 1: VES data interpretation along Lake Mkpitme

VES No	Resistivity (Ωm)	Layers	Thickness (m)	Depth (m)	Curve Type	Inferred Lithology
1	1564.0	1	1.0	1.0	QHK	Top Soil
	464.7	2	3.4	4.4	ρ1> ρ2 >ρ3< ρ4>ρ5	Fine Sand
	33.0	3	6.6	11.0		Clay
	4575.2	4	24.6	34.6		Coarse Sand
	67.6	5	---	---		Clay
2	733.1	1	1.7	1.7	QHK	Top Soil
	705.3	2	8.2	9.9	ρ1> ρ2 >ρ3< ρ4>ρ5	Fine-Medium Sand
	164.2	3	15.6	25.5		Clayey Sand
	4256.3	4	27.5	53.0		Coarse Sand
	206.7	5	---	---		Clayey Sand
3	712.3	1	1.0	1.0	KHK	Top Soil
	1190.6	2	6.5	7.5	ρ1< ρ2 >ρ3< ρ4>ρ5	Medium Sand
	77.1	3	7.3	14.9		Clay
	5129.7	4	14.5	29.4		Coarse Sand
	340.9	5	---	---		Fine-Medium Sand
4	1375.9	1	1.4	1.4	QHK	Top Soil
	448.9	2	9.3	10.7	ρ1>ρ2 >ρ3< ρ4>ρ5	Fine Sand
	132.4	3	3.4	14.2		Clayey Sand
	654.1	4	108.0	122.2		Fine-Medium Sand
	160.1	5	---	---		Clayey Sand
5	1448.1	1	0.8	0.8	QHK	Top Soil
	478.2	2	8.2	9.0	ρ1>ρ2 >ρ3< ρ4>ρ5	Fine Sand
	105.6	3	8.2	17.2		Clay
	1499.9	4	31.5	48.7		Medium Sand
	249.7	5	---	---		Clayey Sand
6	855.9	1	0.8	0.8	QHK	Top Soil
	830.8	2	7.7	8.6	bρ1>ρ2 >ρ3< ρ4>ρ5	Medium Sand
	115.9	3	7.7	16.2		Clayey Sand
	2345.2	4	32.3	48.5		Coarse Sand
	326.0	5	---	---		Fine Sand
7	731.6	1	1.3	1.3	KHK	Top Soil
	753.9	2	6.8	8.1	ρ1< ρ2 >ρ3< ρ4>ρ5	Fine-Medium Sand
	171.1	3	12.8	20.9		Clayey Sand
	3327.0	4	24.9	45.7		Coarse Sand
	289.1	5	---	---		Clayey Sand
8	576.3	1	0.5	0.5	KHK	Top Soil
	1242.6	2	7.8	8.3	ρ1< ρ2 >ρ3< ρ4>ρ5	Medium Sand
	132.7	3	9.6	17.9		Clayey Sand
	2923.3	4	22.4	40.3		Coarse Sand
	344.3	5	---	---		Fine Sand
9	304.6	1	0.2	0.2	KHK	Top Soil
	1119.6	2	8.1	8.3	ρ1< ρ2 >ρ3< ρ4>ρ5	Medium Sand
	95.9	3	8.2	16.5		Clay
	3562.5	4	15.7	32.2		Coarse Sand
	408.9	5	---	---		Fine Sand
10	208.7	1	1.3	1.3	KHK	Top Soil
	5249.2	2	0.9	2.2	ρ1< ρ2 >ρ3< ρ4>ρ5	Coarse Sand
	725.5	3	12.4	14.5		Fine-Medium Sand
	5287.1	4	59.3	73.9		Coarse Sand
	927.2	5	---	---		Medium Sand

Table 2: Summarized geoelectric analysis of Lake Mkpitime area

Layer	Resistivity (Ωm)		Thickness (m)		Depth (m)		Inferred lithology
	Min	Max	Min	Max	Min	Max	
1	208.7	1564	0.2	1.7	0.2	1.7	Top soil
2	448.9	5249.2	0.9	9.3	2.2	10.7	Fine sand, medium – coarse sand
3	33	725.5	3.4	15.6	11.0	25.5	Clay, clayey sand, medium – coarse sand
4	654.1	5287.1	14.5	108	29.4	122.2	Medium – coarse sand
5	67.6	927.2	____	___	___	____	Clayey – coarse sand

Table 3: Summary of the computed aquifer parameters

VES Station	Aquifer Resistivity ρ (Ωm)	Aquifer thickness h(m)	Aquifer depth (m)	Aquifer conductivity $\sigma = 1/\rho$ (Ω^{-1})	Longitudinal conductance $S = \sigma h$ (Ω^{-1})	Transverse resistance $R = h\rho$ (Ωm^2)	Hydraulic conductivity at VES Station K(m/day)	K σ	Transmissivity K σ. R (m²/day)
1	4575.2	24.6	35.6	0.000219	0.005387	112549.9	0.148764	0.000033	3.67
2	4256.3	27.5	53.0	0.000235	0.006463	117048.3	0.159135	0.000037	4.33
3	5129.7	14.5	29.4	0.000195	0.002828	74380.65	0.133706	0.000026	1.93
4	654.1	108	122.2	0.001529	0.165132	70642.8	0.913103	0.001396	98.62
5	1499.9	31.5	48.7	0.000667	0.021011	47246.85	0.421028	0.000281	13.28
6	2345.2	32.3	48.5	0.000426	0.01376	75749.96	0.27748	0.000118	8.94
7	3327.0	24.9	45.7	0.000301	0.007495	82842.3	0.200245	0.00006	4.97
8	2923.3	22.4	40.3	0.000342	0.007661	65481.92	0.225926	0.000077	5.04
9	3562.5	15.7	32.2	0.000281	0.004412	55931.25	0.187868	0.000058	3.24
10	5287.03	59.3	73.9	0.000189	0.011208	313525	0.129989	0.000025	7.84
Average	**3356.03**	**36.07**	**52.95**		**0.024536**	**101539.89**	**0.279724**		**15.19**

Although, a number of different factors can influence resistivity measurements, but in this study, some standard ranges were used to assess groundwater chemistry/quality. Jansen (2011) asserted that "resistivity ranges of 30-50 Ωm or higher, suggest sandy zones filled with air or freshwater, while resistivity ranges of 20-30 Ωm represent soil that are clay-rich, and typically 10 Ωm or less demonstrates sandy zones filled with brackish or saline water". Thus, the results from this study reveals that the aquifer is freshwater because all the resistivity values measured were above 30 Ωm. Table 2 presents the summarized geoelectric analysis of Lake Mkpitime area. Representative VES curves, obtained from VES data interpretation (computer iteration) are presented in Figure 3a, b, c. Two VES model curves were identified. They include QHK and KHK respectively. Analysis revealed that both model curves constitute 50 % each in the study area (Table 1). As noted by Chinyem (2024), "the occurrence of different field curves indicates a variation in layer properties across the study locations, which are due to geologic processes such as fracturing, weathering and other processes". The geoelectric sections (Figures 4a, b), constructed from VES analysis corroborates with the corresponding borehole lithologic section. Comparison was done on the boreholes log (obtained from drilled well) with the corresponding geoelectric sections. The result revealed a lateral lithologic heterogeneity, which is a result of groundwater variations in sediment grain sizes. The implication of this that the aquifer (groundwater) has some level of protection from the lithologic units identified (lateritic sand, clay, clayey sand, fine sand). Figure 7 illustrates the longitudinal conductance (S) map. It shows a range of 0.002828-0.165132 Ω^{-1} in VES 3 and VES 4 locations, respectively, implying a poor weak protective capacity of the aquifer to contamination. The S rating, suggested by Oladapo et al (2004), as shown in Table 4, was used to classify the protective capacity/vulnerability of the aquifer, Figure 8 shows the aquifer transverse (R) map. The high R range of 47,246.85-313,525 Ωm^2 with an average of 101539.89 Ωm^2, imply good groundwater potential for productive borehole drilling for local water supply to communities. Similarly, Figure 9 shows the aquifer transmissivity (T) map. The computed T values ranged from 1.93-98.62 m^2/day, with an average value of 15.19 m^2/day imply, poor to intermediate transmissivity, according to the classification scheme of Krasny (1993) as shown in Table 5. Figure 10 illustrates the hydraulic conductivity (K). The computed K ranged from 0.129989-0.913103 m/day. The soil materials (surface) ranged from lateritic clay/top soil to fine sand. The K rating, suggested by Bouwer (1978) was used for the classification of the K standard for soil materials, Generally, there is high degree of variability in aquifer thickness as it ranged from 14.5 to 108 m in the fourth geoelectric layers (VES 3 and VES respectively).

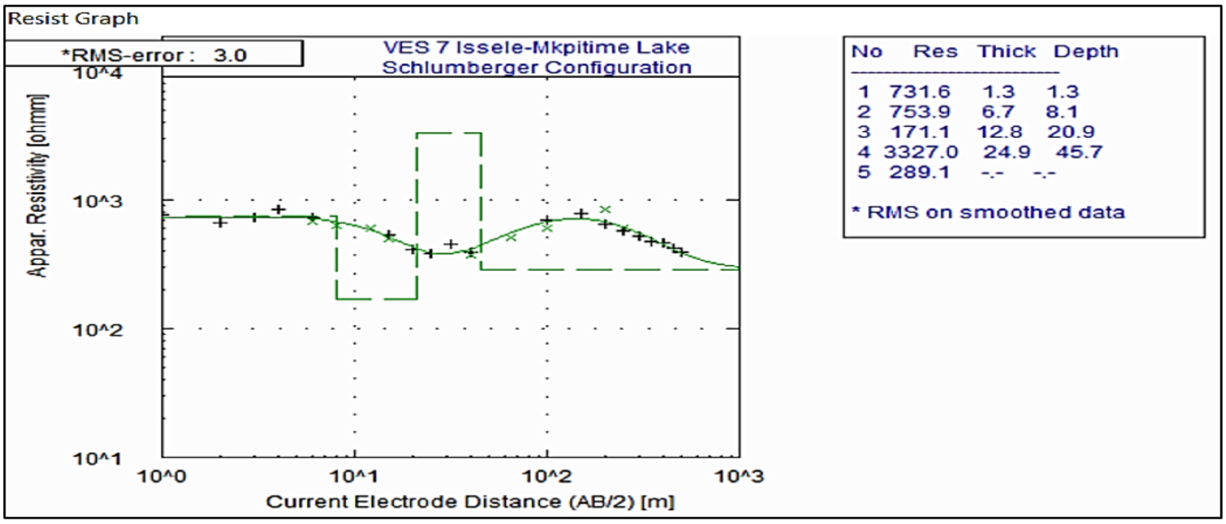

Figure 3: Representative VES Curve (VES 7)

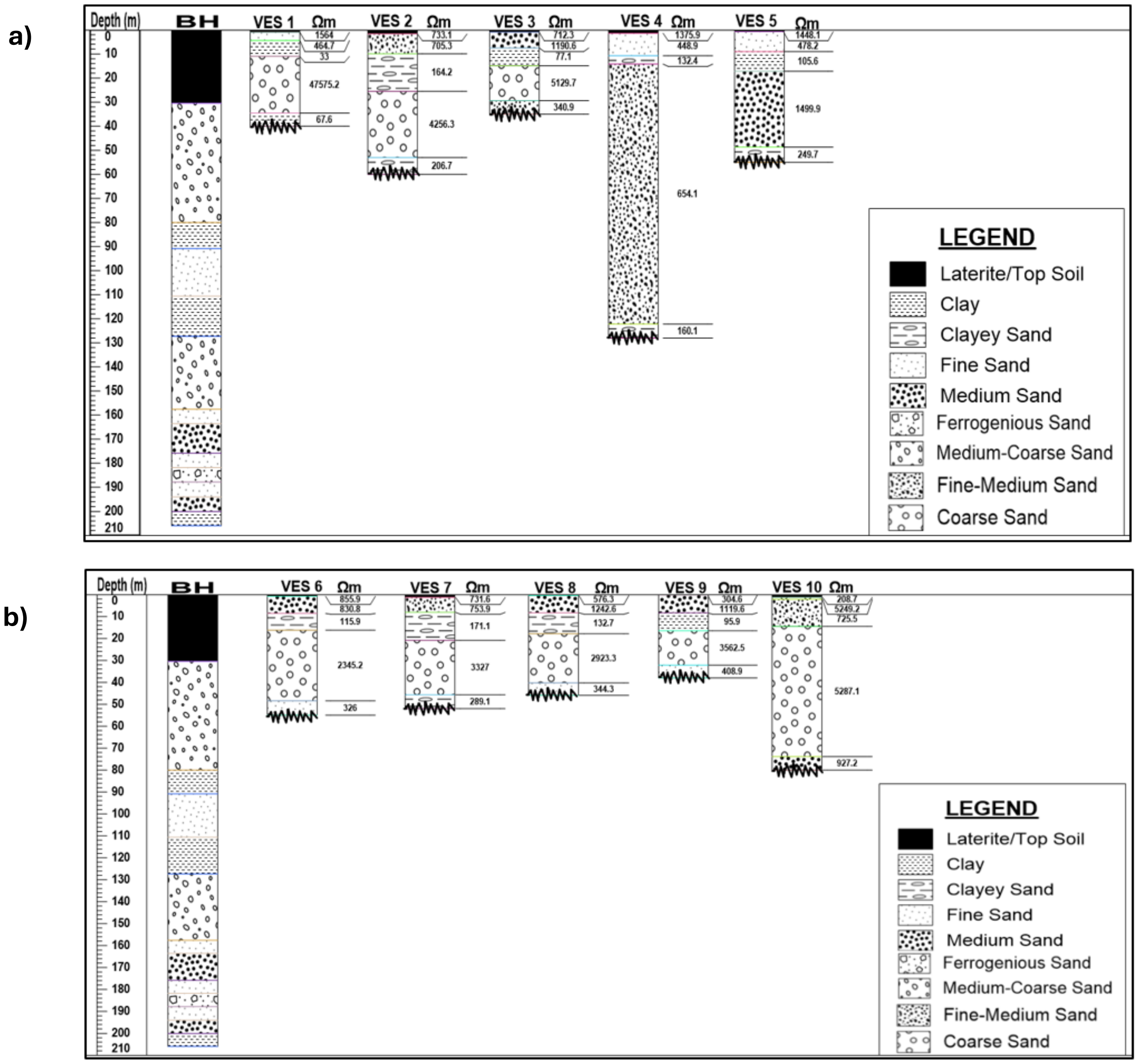

Figure 4: Geoelectric Section of (a) VES 1-5 and (b) VES 6-10

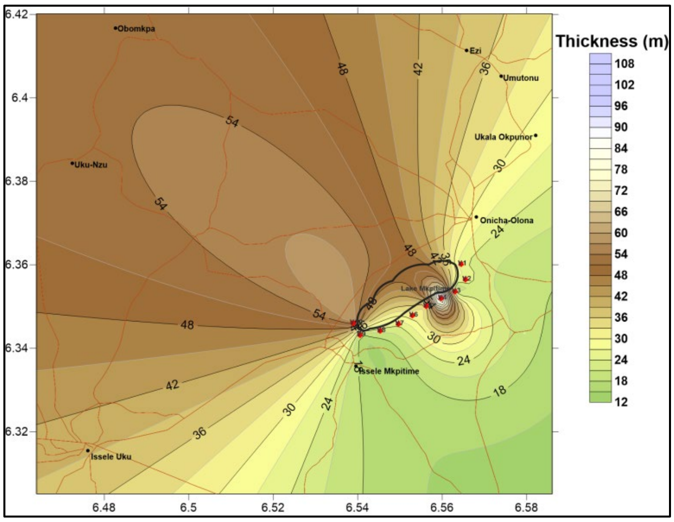

Figure 5: Aquifer thickness map

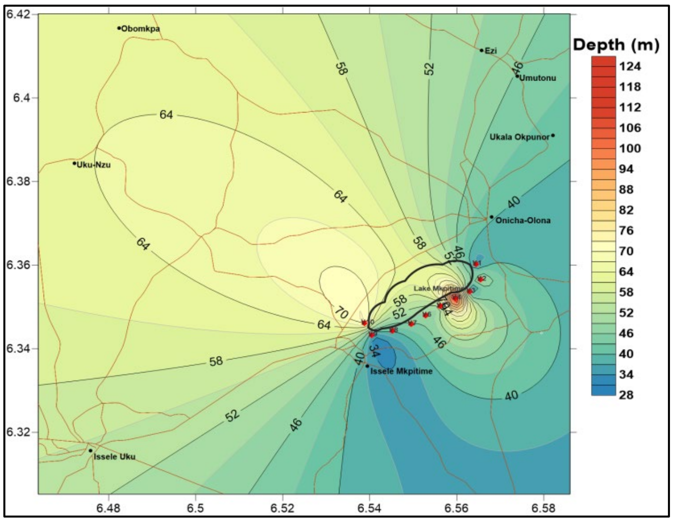

Figure 6: Depth to aquifer map

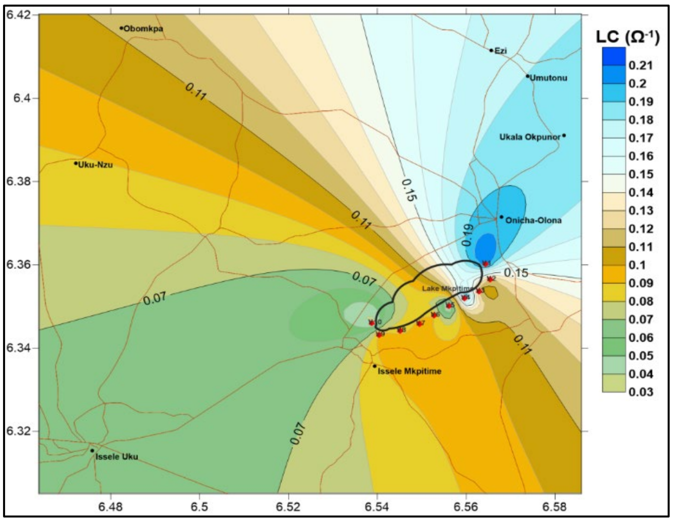

Figure 7: Longitudinal Conductance map

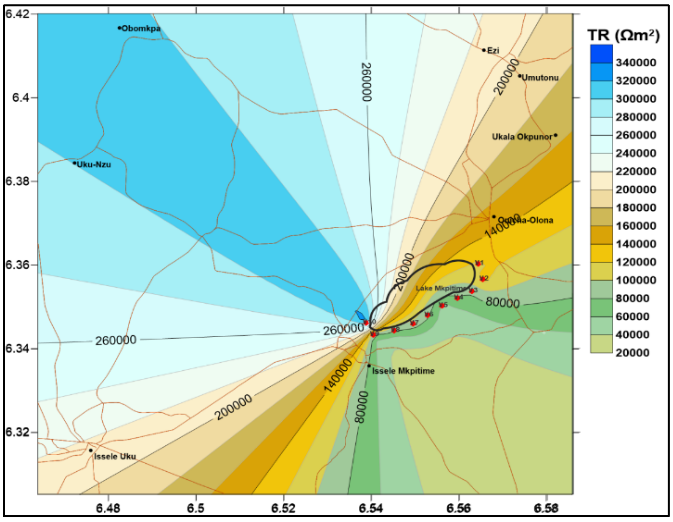

Figure 8: Transverse resistance map

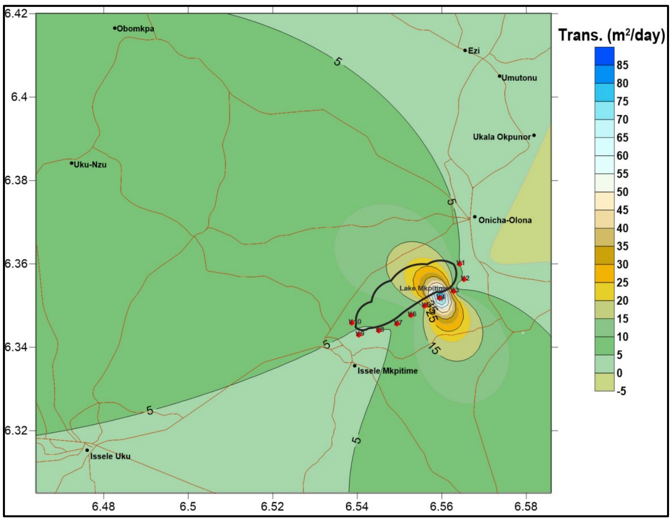

Figure 9: Aquifer transmissivity map

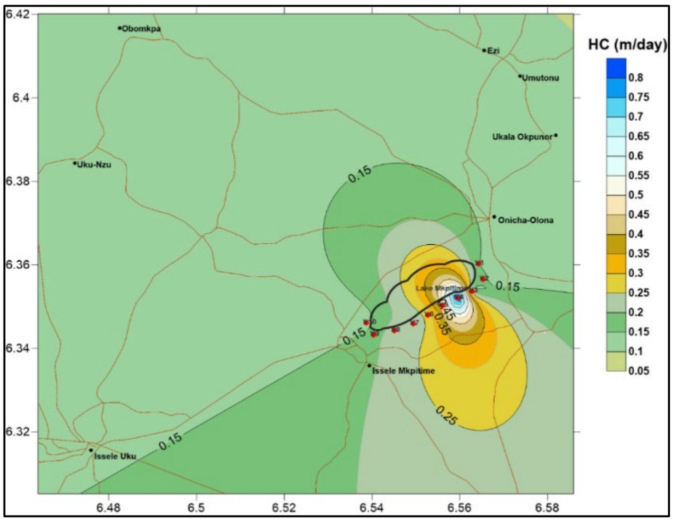

Figure 10: Hydraulic conductivity map

Table 4: Modified longitudinal unit conductance/protection capacity rating (Oladapo et al., 2004**)**

Longitudinal Conductance(Ω^{-1})	Protective Capacity rating
>10	Excellent
5-10	Very Good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor

4.2 GROUNDWATER QUALITY ASSESSMENT

The results of physical and chemical parameters of water from Lake Mkpitime (SW) and groundwater (GW) from surrounding boreholes (wells) are tabulated in Tables 6a, b, c and 7a, b, c respectively. The chemical analysis reveals slight variations in chemical constituents of both lake water sample (Tables 6a, b, c) and groundwater samples (Table 7a, b, c).

The pH of a water body indicates the quality of the water and the level of contamination (Yisa and Jimoh, 2010). The pH of the lake samples ranged from 5.02-6.14, with an average value of 5.7, while that of the groundwater ranged from 5.82-6.83 with an average value of 6.2, revealing that the water is slightly acidic in nature and above the World Health Organization (WHO, 2011) acceptable level for drinking water. The elevated water acidity could be due to anthropogenic activities and indiscriminate wage disposal, as well as weathering process that occur within the aquifer horizons. It is an indication of hydroxide ion depletion in such water samples in relation to abundant hydrogen ions present in the samples. The pH profile shown in Figure 11a indicates an almost same range in the lake samples, while in the groundwater, there was a decrease towards GW3 (Figure 11b) revealing an interaction between the lake and the surrounding groundwater.

Table 5: Classification of aquifer transmissivity (Krasny, 1993)

T(mday^{-2})	**Designation**	**Groundwater Supply Potential**
> 1000	Very High	Withdrawal of great regional importance
100 – 1000	High	Withdrawal of lesser regional importance
10 – 100	Intermediate	Withdrawal of local water supply (small communities, plants etc)
1 – 10	Low	Smaller withdrawals for local water supply (private consumption)
0.1 – 1	Very low	Withdrawals for local water supply with limited consumption
< 0.1	Impermeable	Sources for local water supply are difficult, if possible to ensure

Table 6a: Results of hydrochemical parameters of Issele- Mkpitime Lake (wet season)

Location	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
SW1	N $6^0$21'46'' E $6^0$33'48''	6.2	49.1	24	91.4	27	117.8	29.3	455	7.12	415	2385
SW2	N $6^0$21'43'' E $6^0$33'42''	5.12	25	10.4	90.1	26.9	114.5	26.5	455	7.12	415	2385
SW3	N $6^0$21'38'' E $6^0$33'21''	5.98	18.4	9.7	82.2	25.8	100.5	23.8	455	1.7	451	2590
SW4	N $6^0$21'22'' E $6^0$33'14''	6.28	29.5	13.2	74.3	25.1	96.2	22.6	540	7.12	415	2385
SW5	N $6^0$21' 14'' E $6^0$32' 56''	5.7	40.3	18.6	60.2	24.4	93.8	20.2	540	10.44	392	2612
SW6	N $6^0$21'06'' E $6^0$32'49''	6	41.6	20.3	54.01	23.8	88.5	17.5	540	10.44	392	2612
SW7	N $6^0$20'54'' E $6^0$33'41''	6.02	25.4	30.1	45.1	22.5	81.6	14.5	540	10.44	392	2612
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

Table 6b: Results of hydrochemical parameters of Issele- Mkpitime Lake (dry season)

Location	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
SW1	N 6⁰ 21'46'' E 6⁰ 33'48''	6.08	50.5	25.8	92.8	31	119.6	31.7	475	5.02	427	2453
SW2	N 6⁰21'43'' E 6⁰ 33'42''	4.92	26.8	15.5	91.92	29.9	115.9	28.5	475	5.02	427	2453
SW3	N 6⁰21'38'' E 6⁰ 33'21''	5.62	24.8	11.9	84.02	29.8	104.5	25.4	475	1.1	473	2612
SW4	N 6⁰21'22'' E 6⁰ 33'14''	5.43	31.5	17.3	76.12	27.32	99.4	24.2	556	5.02	427	2453
SW5	N 6⁰21' 14'' E 6⁰ 32' 56''	5.48	43.9	23.5	62.4	26.4	96.8	22.2	556	6.5	412	2756
SW6	N 6⁰21'06'' E 6⁰ 32'49''	5.66	43.8	22.7	58.03	25.2	92.3	19.1	556	6.5	412	2756
SW7	N 6⁰20'54'' E 6⁰ 33'41''	5.64	27.8	32.5	49.9	23.7	82.8	16.5	556	6.5	412	2756
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

Table 6c: Results of hydrochemical parameters of Issele- Mkpitime Lake (seasonal average)

Location	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
SW1	N 6⁰ 21'46'' E 6⁰ 33'48''	6.14	49.8	24.9	92.1	29	118.7	30.5	465	6.07	421	2419
SW2	N 6⁰21'43'' E 6⁰ 33'42''	5.02	25.9	12.95	91.01	28.4	115.2	27.5	465	6.07	421	2419
SW3	N 6⁰21'38'' E 6⁰ 33'21''	5.8	21.6	10.8	83.11	27.8	102.5	24.6	465	1.4	462	2601
SW4	N 6⁰21'22'' E 6⁰ 33'14''	5.84	30.5	15.25	75.21	26.21	97.8	23.4	548	6.07	421	2419
SW5	N 6⁰21' 14'' E 6⁰ 32'56''	5.59	42.1	21.05	61.3	25.4	95.3	21.2	548	8.47	402	2684
SW6	N 6⁰21'06'' E 6⁰ 32'49''	5.83	42.7	21.35	56.02	24.5	90.4	18.3	548	8.47	402	2684
SW7	N 6⁰20'54'' E 6⁰ 33'41''	5.83	26.6	32.3	47.5	23.1	82.2	15.5	548	8.47	402	2684
Average		**5.7**	**34.2**	**19.7**	**72.3**	**26.3**	**100.3**	**23**	**512.4**	**6.43**	**418.7**	**2558.6**
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

Table 7a: Results of hydrochemical parameters of Issele- Mkpitime groundwater (wet season)

Location	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
GW1	N 6⁰ 19' 58'' E 6⁰ 33' 42''	6.99	8.1	18.5	16.01	5.01	48.05	5.01	13.88	6.94	8.5	5.1
GW2	N 6⁰ 20' 25'' E 6⁰ 34' 01''	6.18	9.5	12.04	19.5	3.8	51.7	6.1	11.3	2.18	1.2	2.6
GW3	N 6⁰ 20' 42'' E 6⁰ 33'08''	6.04	9.8	10.5	20.1	16.5	60.5	6.5	13.5	1.39	3.4	8.4
GW4	N 6⁰21'25'' E 6⁰ 34' 20''	6.18	9.6	14.8	28.5	19.9	69.4	10.01	17.5	2.5	2.58	9.2
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

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Table 7b: Results of hydrochemical parameters of Issele- Mkpitime groundwater (dry season)

Locations	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
GW1	N 6⁰ 19' 58" E 6⁰ 33' 42"	6.67	12.06	20.12	16.93	4.32	50.07	5.71	15.4	6.5	9.5	6.0
GW2	N 6⁰ 20' 25" E 6⁰ 34' 01"	6.1	10.74	13.86	21.3	4.24	53.1	7.38	13.1	1.6	1.8	3.4
GW3	N 6⁰ 20' 42" E 6⁰ 33'08"	5.6	10.56	11.1	21.94	18.1	61.58	7.58	22.5	1.01	4.6	9.6
GW4	N 6⁰21'25" E 6⁰ 34' 20"	5.5	10.72	15.7	31.52	20.20	70.62	11.61	22.5	1.58	3.84	10.8
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

Table 7c: Results of hydrochemical parameters of Issele- Mkpitime groundwater (seasonal average)

Location	Coordinates	Parameters										
		pH	EC (µS/cm)	TDS (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Mg (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Cl^- (mg/l)
GW1	N 6⁰ 19' 58" E 6⁰ 33' 42"	6.83	10.08	19.31	16.47	3.86	49.06	5.36	14.64	6.72	9	5.55
GW2	N 6⁰ 20' 25" E 6⁰ 34' 01"	6.14	10.12	12.95	20.4	4.02	52.4	6.74	12.2	1.89	1.5	3
GW3	N 6⁰ 20' 42" E 6⁰ 33'08"	5.82	10.18	10.8	21.02	17.3	61.04	7.04	15.01	1.17	4	9
GW4	N 6⁰21'25" E 6⁰ 34' 20"	5.84	10.16	15.25	30.01	20.05	70.01	10.81	20	2.04	3.21	10
WHO (2011) limit		**6.5-8.5**	**1000**	**600**	**200**	**30**	**200**	**150**	**250**	**50**	**250**	**250**

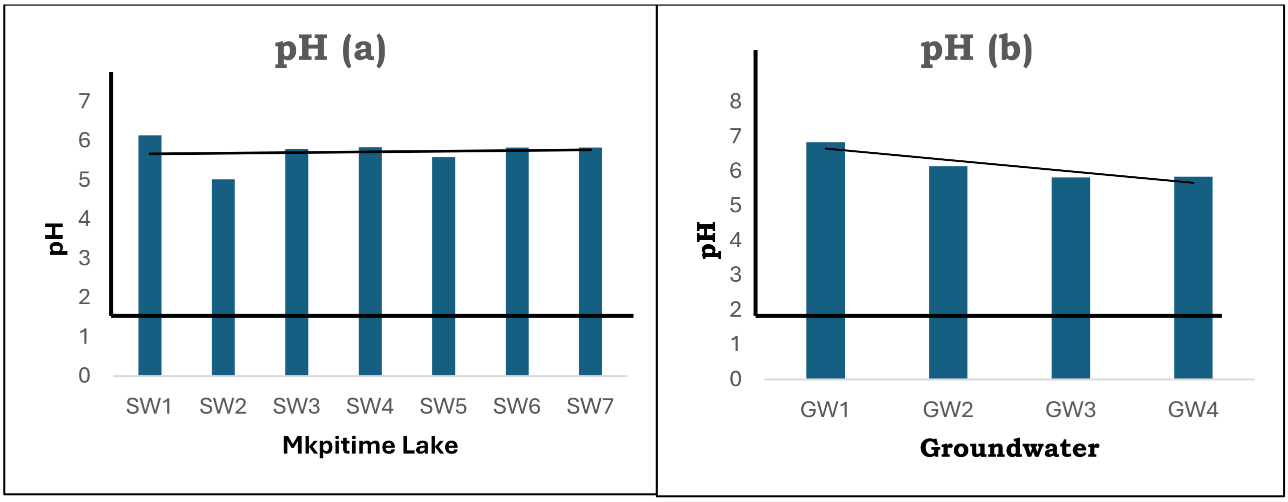

Figure 11: pH concetration along (a) Lake samples (b) groundwater wells

The EC is an important parameter that is linked to the salinity of water. Gamal et al. (2003) noted that "the EC is a measure for the determination of the total salt content of water by the passage of electricity through the sample". It indicates dissolved substances, chemicals, and minerals in water. The EC measured for the lake ranged 21.6-49.8 µS/cm, with an average of 34.2 µS/cm, while that of the groundwater ranged from 10.8-10.18 µS/cm with an average of 10.1 µS/cm. This value range of EC implies that, there is low level of salinity, dissolved minerals and chemicals in the water samples. The observed EC values for both samples are below WHO (2011) acceptable limit, and therefore, reflects their suitability for various application (domestic and agricultural needs).

4.2.1 TOTAL DISSOLVED SOLIDS (TDS)

TDS of water sample reflects the weight of residual materials which are deposited, after the samples have evaporated (Ebong et al. 2016). TDS for the lake and groundwater samples ranged from 10.8-31.3 mg/l and 10.8-19.31 mg/l respectively, thus reflecting a freshwater category, according to the classification of Freeze and Cherry (1979) in Table 8. The observed TDS values are within WHO (2011) acceptable limit for domestic and agricultural use. TDS profile in Figure 12a, b indicates an increase towards SW7 for the lake and a decrease towards GW3 for groundwater. There is a strong correlation between the TDS results and the resistivity results. The low TDS (< 35 mg/l) observed in the area, correlates with zones with high aquifer resistivities, characteristics of freshwater sands and gravels with low clay intercalation, reflecting fresh nature of the groundwater within the area.

Table 8: Nature of groundwater, using TDS values (Freeze and Cherry, 1979)

Water class	TDS (mg/l)
Fresh water	<1000
Brackish water	1000-10,000
Salty water	10,000-100,000
Sea water	> 100,000

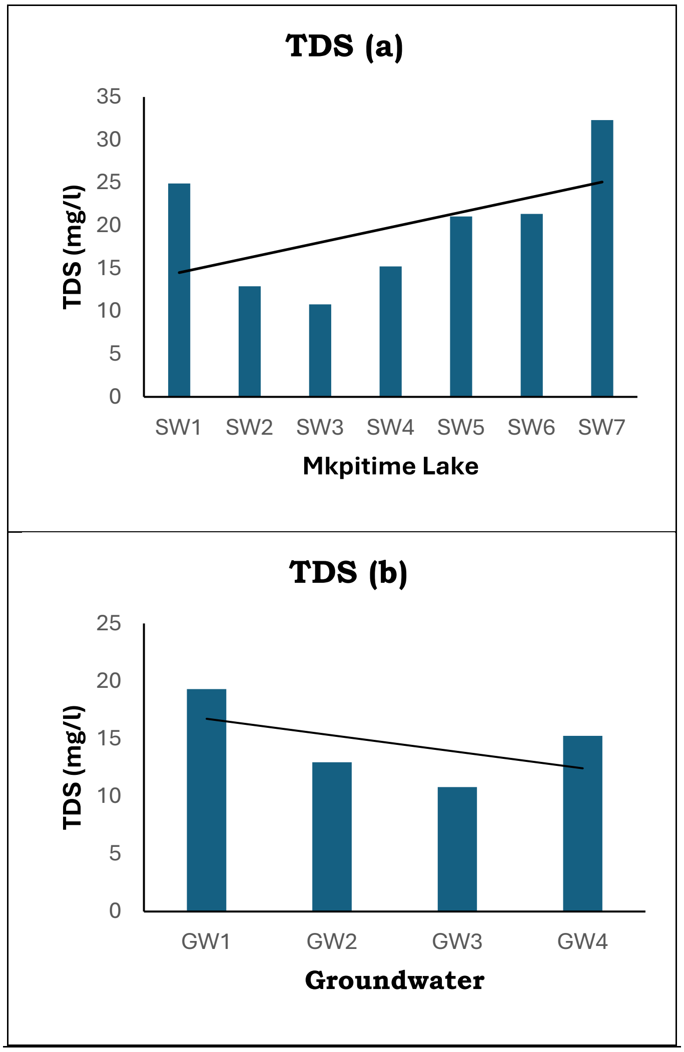

Figure 12: TDS concetration along (a) Lake samples (b) groundwater wells

4.2.2 MAJOR CATIONS

The investigated concentration of cations: Na^+, Ca^{2+}, Mg^{2+} and K^+ in the study area vary respectively. For the main cations, Ca^{2+} is the most dominant, followed by Na^+, K and Mg^{2+} while chloride and bicarbonate are the most dominant anions, followed by sulphate.

The measured Na^+ concentrates in the lake samples (SW) ranged from 47.5-92.1 mg/l, while that of groundwater samples (GW) ranged from 16.47-30.01 mg/l. Elevated levels of Na^+ in both samples may be attributed to clay/shale leaching process in the aquifer unit. The profiles of Na in Figure 13a, b shows a fall in concentration towards SW7 in the lake samples, while a rise towards GW4 in the groundwater samples. Nevertheless, Na^+ concentration (Na^+ < 200 mg/l) in both the lake and groundwater samples are within the WHO (2011) acceptable level for drinking and agricultural use.

Ca^{2+} concentration measured for the lake samples ranged from 82.2-118.7 mg/l. High Ca^{2+} in the lake sample may be due to leaching of calcium containing minerals around the path of the waters flowing inside the lake. The profiles of Ca^{2+} in Fig. 14a, b show a decrease towards SW7 in the lake and an increase towards GW4 in the groundwater. The Ca^{2+} concentration of both the lake water and groundwater is within the approved WHO (2011) approved unit (200 mg/l) for drinking and agricultural needs.

The concentration profiles of K^+ in Fig. 15a, b indicate a slight decrease towards SW7 in the lake samples, and an increase towards GW4 in groundwater. The K^+ concentrations in both lake and groundwater samples are within the WHO (2011) guideline value (30 mg/l). High K^+ concentration is principally due to silicate weathering processes, as well a human activity (Ohwoghere-Asuma et al., 2020; Gamal et al., 2023).

Mg^{2+} concentration measured for the lake samples ranged from 15.5-30.5 mg/l, while that observed in the groundwater samples ranged from 5.36-10.81 mg/l, and they are found to be within the acceptable limit (150 mg/l) of WHO (2011) for domestic and agricultural use. The concentration profiles in Figure 16a, b show a decrease in Mg^{2+} concentration towards SW7 in the lake and an increase towards GW4 in the groundwater. Elevated concentrations in the water samples are usually associated with weathering of magnesium minerals around the pathways of water flowing inside the lake, as well as leaching/dissolution process in the water.

In general, increase in cations (Na^+, Ca^{2+}, K^+ and Mg^{2+}) concentrations in both lake and groundwater samples, can be attributed to the composition of the dominant ions in the major rocks present in the sedimentary environment. Hem (1989) and

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Ebong et al. (2016) asserted that “the abundance of Na^{+}, Ca^{2+} and Mg^{2+} in groundwater are probably as a result of fall outs from weathering processes of calcite and silicate enriched rocks”. Moreso, the application of soil fertility products (chemicals), as well as indiscriminate waste water disposal can cause elevated cation concentration in groundwater, especially if the vadose zone and the aquifer horizon lack the ability to filter or weaken the vertical passage, through preferential pathways of such contaminants in the vadose zone. Earlier, Akpan et al. (2013) and Ebong et al. (2016), reported similar cases of increased cation concentrations (Ca^{2+}, Mg^{2+} Na^{+} and K^{+}) in Ikom and Abi areas, respectively, of the Mamfe Embayment.

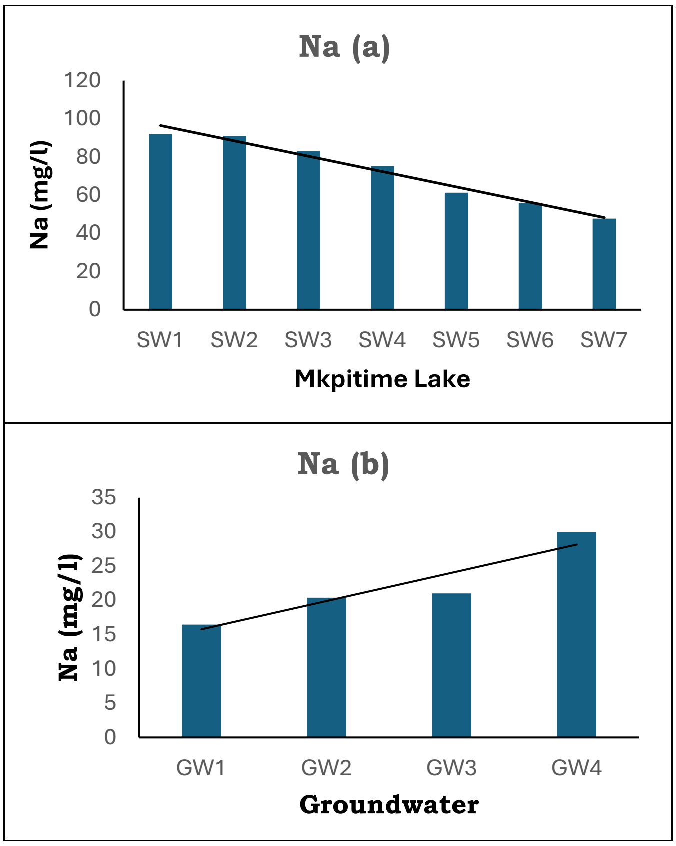
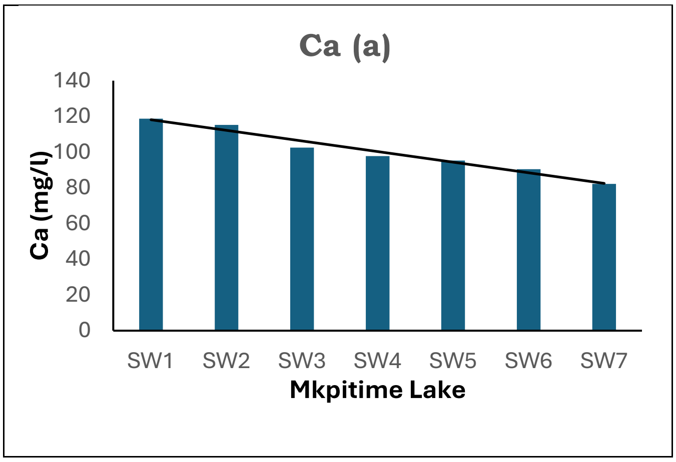


Figure 13: Na^{+} concetration along (a) Lake samples (b) groundwater wells



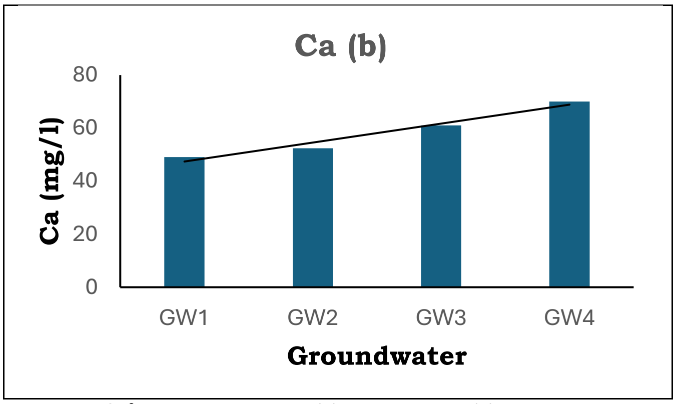


Figure 14: Ca^{2+} concetration along (a) Lake samples (b) groundwater wells

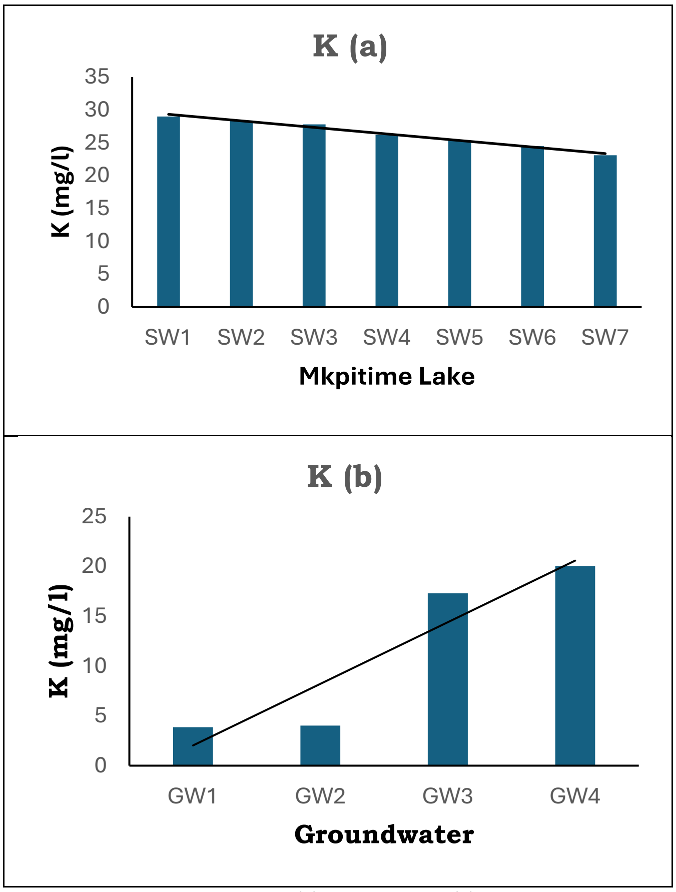
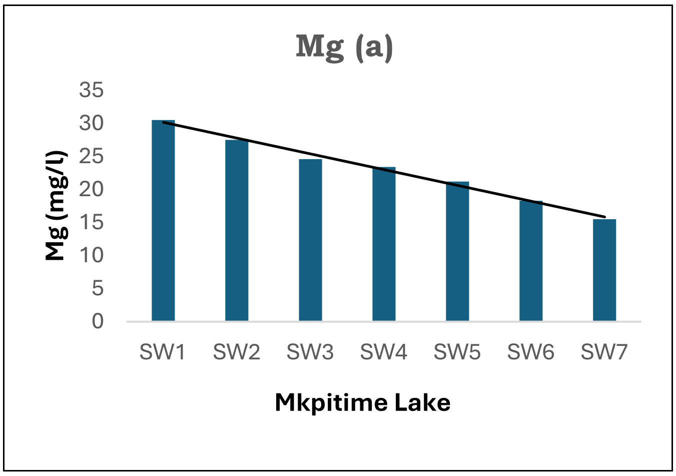


Figure 15: K^{+} concetration along (a) Lake samples (b) groundwater wells



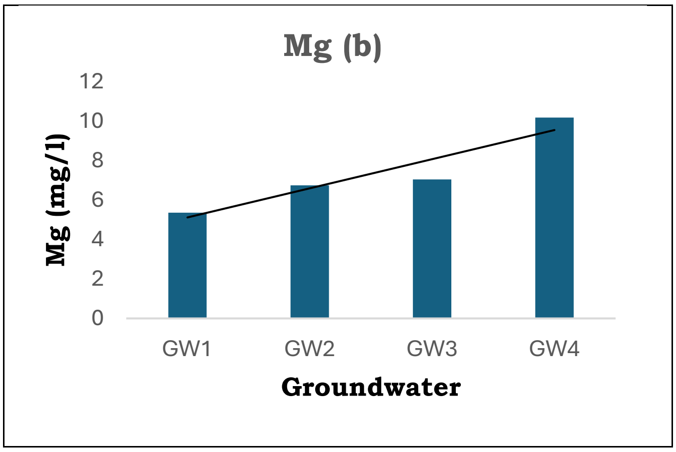


Figure 16: Mg^{2+} concetration along (a) Lake samples (b) groundwater wells

4.2.3 MAJOR ANIONS

Concentrations of major anions (Cl^-, HCO_3^-, SO_4^{2-} and NO_3^-) in the study area vary. The chloride (Cl^-) content observed in the lake samples ranged from 2419-2684 mg/l, while that of groundwater samples ranged from 3.0-10.0 mg/l. the groundwater values were lower than the WHO (2011) limit for drinking, while that of the lake exceeded the WHO (2011) permissible limit (250mg/l). High Cl^- observed may be attributed to the use of fertilizers, indiscriminate waste disposal and land fill leachate around the lake. The concentration profiles in Figure 17a, b show a slight increase towards SW7 for the lake samples and a rise towards GW4 for the groundwater samples.

Bicarbonate (HCO_3^-) concentration ranged from 465-548 mg/l for lake samples while 12.2-20.0 mg/l was observed for the groundwater samples. The observed values for the lake samples exceeded the WHO (2011) permissible limit (250 mg/l) for drinking, while that of the groundwater is lower than the standard. High HCO_3^- may be due to interaction of the water flowing into the lake with some rocks. The profiles in Figure 18a, b show an increase towards SW7 and GW4 in the lake and groundwater samples respectively.

High SO_4^2 was observed in the lake samples as it ranged from 402-421 mg/l, while a low concentration was observed for the groundwater samples. Elevated levels of SO_4^{2-} may be due to the washing/dissolution of sulphate-bearing minerals in the area. Figure 19a, b shows a slight increase in SO_4^{2-} profile towards SW7 while decrease towards GW4 for groundwater samples.

Nitrate (NO_3^-) concentration observed for the lake samples ranged from 1.4-8.47mg/l, while that observed for groundwater ranged 1.17-6.72 mg/l. the observed values for both the lake and groundwater, respectively, were below (within) WHO (2011) acceptable limit (50 mg/l). The low NO_3^- concentration may be due to denitrification influence in the area. The concentration profiles in Figure 20a, b show a rise towards SW7 in the lake and decrease towards GW4 in the groundwater.

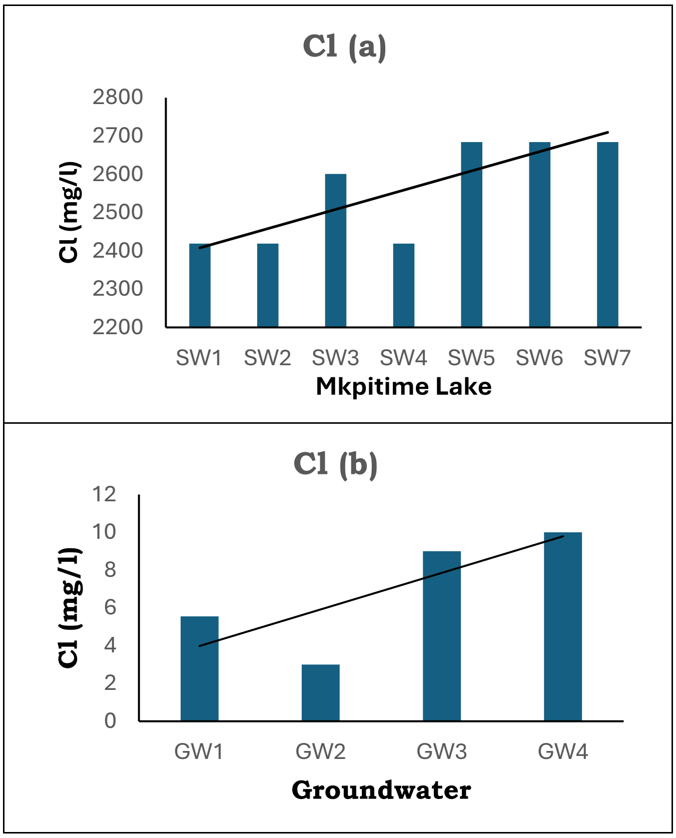


Figure 17: Cl^- concetration profile along (a) Lake samples (b) groundwater wells

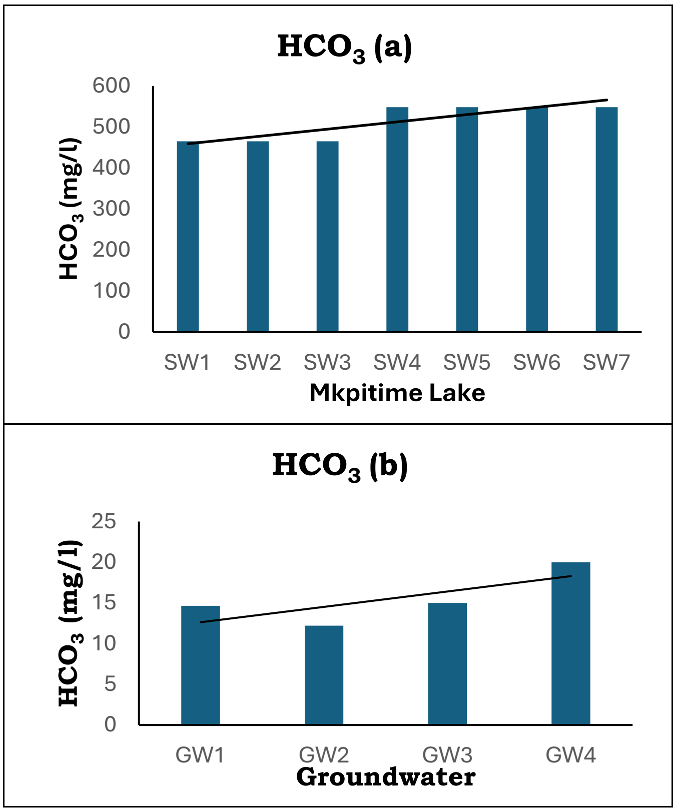


Figure 18: HCO_3^- concetration profile along (a) Lake samples (b) groundwater wells

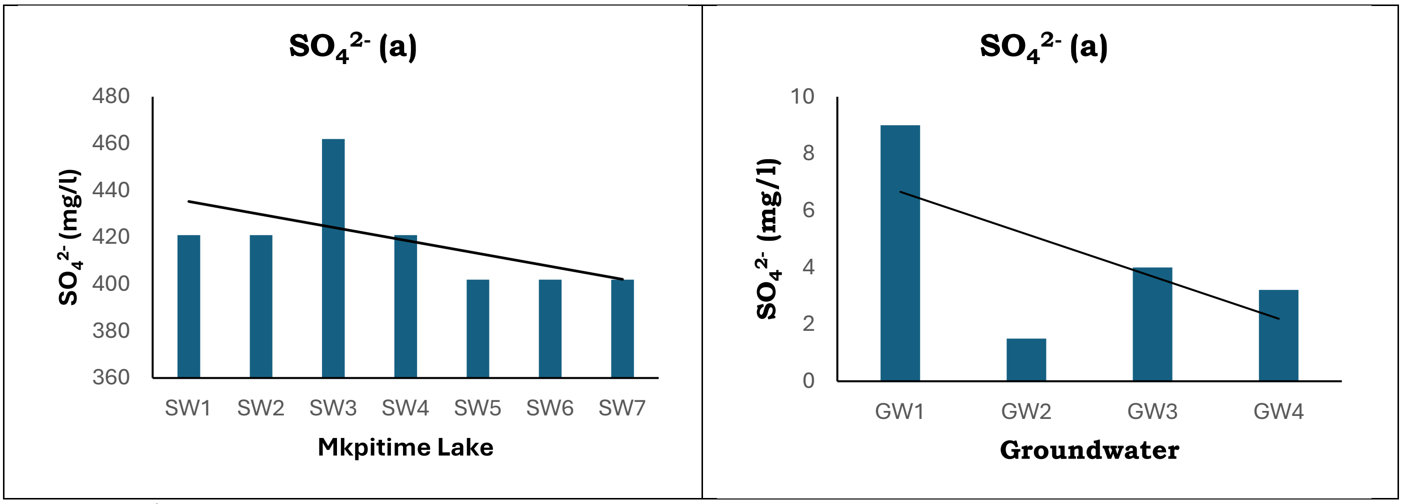


Figure 19: SO_4^{2-} concetration along (a) Lake samples (b) groundwater wells

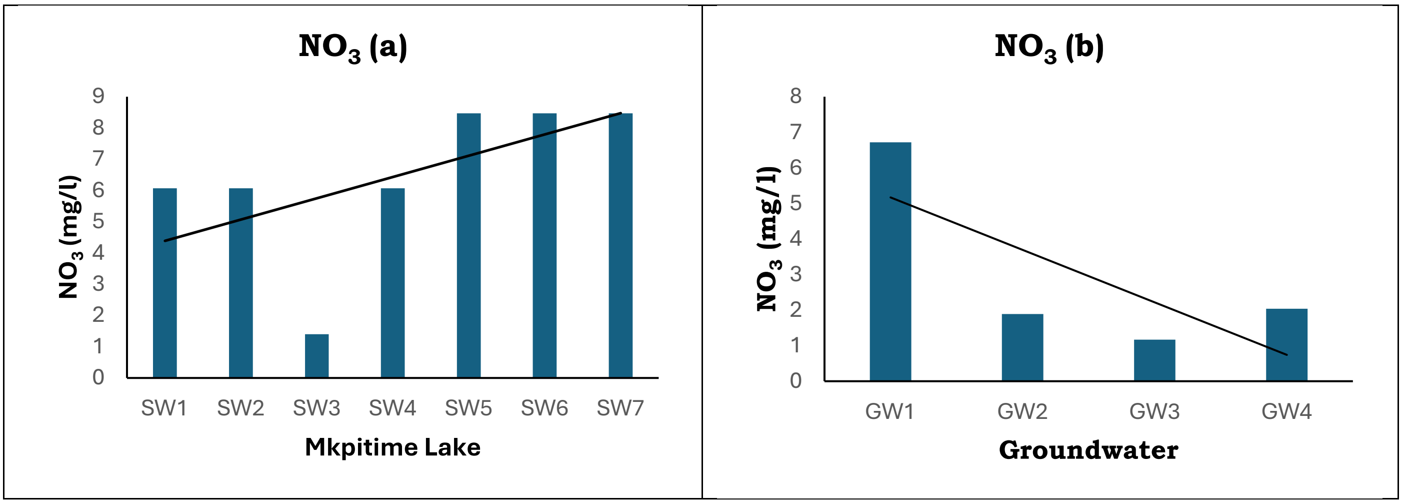


Figure 20: NO_3^- concetration profile along (a) Lake samples (b) groundwater well

Analysis of Piper (1944) trilinear diagram for the lake and groundwater samples are shown in Figures 21a, b respectively. Piper diagram examines the distribution and geochemical genesis of water by graphically correlating the cations and anions constituents of water. Hence, it can be used to identify the hydrogeochemical facies of water bodies. The Piper diagram was constructed, using surfer software. The diagram showed clear dominance of Ca^{2+} concentration in both water facies.

This observation is in line with the reports by Handa (1979), Akpan et al. (2013) and Ebong et al. (2016), to indicate water facies with sufficient recharge from fresh water as well as water with temporary hardness. The relative cation abundance, with respect to their concentrations in is the order of Ca^{2+} > Na^+ >K^+ > Mg^{2+} for both water sources, while those of the anions are in the order of Cl^- > HCO_3^- > SO_4^{2-} >NO_3^- for the lake, while the groundwater samples have order of HCO_3^- >Cl^->SO_4^{2-} >NO_3^-. All samples (lake and groundwater) were observed to be of mixed types of water, with little attributes of sodium-chloride type, indicating a strong lake water influence.

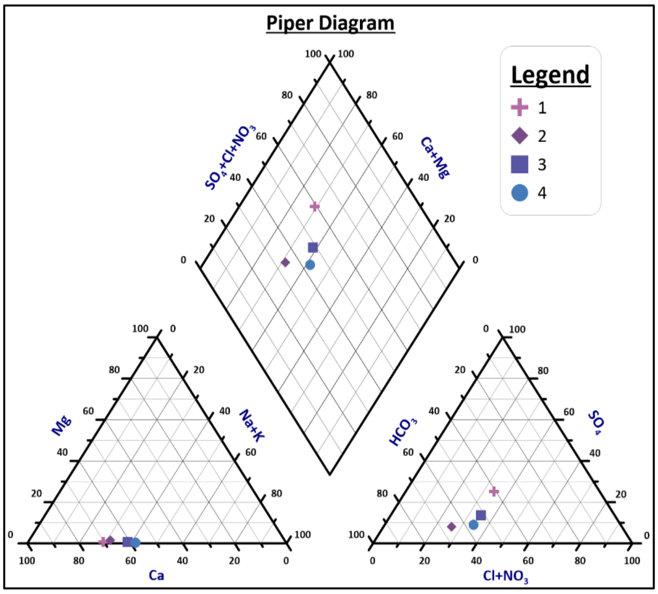


Figure 21 (a) : Piper trilinear diagram for Lake water

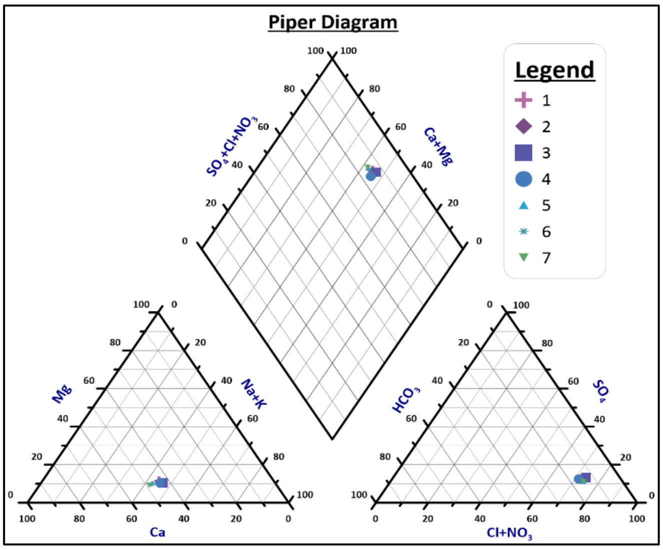


Figure 21 (b) : Piper trilinear diagram for groundwater samples

CONCLUSION

The groundwater quality assessment around Lake Mkpitime, NE of NDB, Nigeria, was carried out using an integrated geophysical and hydrochemical approaches. The geophysical result revealed vertical and lateral sedimentary units' distribution of the BF (sand with clay intercalation), which constitutes the aquifer unit in the area. The study delineated five geoelectric layers which include topsoil, clay, clayey sand/fine sand, fine-medium sand, and coarse sand. Due to the presence of clay in some areas, the aquifer system is confined in some areas and unconfined in others. The aquifer thickness ranged from 12-108 m, with depth range of 28-124 m. The aquifer S, R, T and K ranged from 0.3-0.213 Ω^{-1}, 47246.85-313525 Ωm^2, 1.94- 98.62 m^2/day and 0.129989-0.913103 m/day respectively, indicating a low to moderate protective capacity, as well as low to intermediate groundwater potential. With respect to the hydrochemical approach, the groundwater assessment was done based on the analysis of seven lake samples and four groundwater samples (boreholes) randomly distributed during the wet and dry seasons within the study area.

Generally, both water sources (lake and groundwater) are slightly acidic and have low sodium hazards. The Ca^{2+}, Na^+, K^+, Mg^{2+}, NO_3^- and TDS concentrations are within the WHO permissible limits for both water sources. The pH, Cl^-, HCO_3^- and SO_4^{2-} concentrations are higher than the maximum permissible limits for the lake (surface water), which may be attributed to anthropogenic effects. However, the results have shown that both lake and groundwater are safe and suitable for agricultural purposes and industrial use, while the groundwater is acceptable for domestic needs. Hence, from this study, the groundwater quality is safe for human consumption and can be used for domestic purposes, agricultural and industrial sustainable use respectively.

Although, this current work is limited due to scarcity of hydrochemical data, it can serve as an initial guide to groundwater quality assessment, availability and distribution in the area. Furthermore, these approaches are significant as they can give valuable information for the assessment of groundwater chemistry as well as its hydrogeologic setting in the area. In order to obtain an acceptable groundwater quality for sustainable use, there is a need to adopt regulations that will help to protect and manage the aquifer (groundwater). Moreso, proper groundwater abstraction and use is important to prevent lake water incursion, which might eventually degrade the groundwater quality in the area.

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