Original Research Article

Assessing the Impact of Leachate Infiltration from Dumpsites into the Groundwater System of Agu-Awka and Environs, Southeastern Nigeria.

Abstract

This study was carried out in Agu-Akwa, Southeastern Nigeria, to investigate the impacts of leachate infiltration from dumpsites on the groundwater system using an integrated approach that combines geotechnical, geochemical, and geophysical methods. The research methodology involves a preliminary study through literature reviews, followed by integrated geotechnical, geophysical, and geochemical approaches to achieve its aim. The geotechnical analysis identifies two major soil types, sand and shale, with an average hydraulic conductivity of 0.011cm/s, ranging from 0.007 to 0.022cm/s. The soils are generally poorly graded. The interpretation of geo-electric layers reveals water-saturated sandstones and weathered shales, the primary aquifers, with average depth, thickness, resistivity, and transmissivity values of 55.01m, 26.45m, 327.09 Ωm, and 143.44m^2/day, respectively. The area's aquifer protective capacity and aquifer vulnerability index were found to be poor to good and low to moderate, respectively. Hydrogeochemical analysis revealed elevated levels of pH (5.10 – 6.80), Biological Oxygen Demand (104 – 488), Chemical Oxygen Demand (23.68 – 102.08), Mercury (0.040 – 0.253mg/L), Chromium (0 – 0.321mg/L), and Arsenic (0.004 – 0.218mg/L) above permissible limits of the World Health Organization for drinking water. The result of the study reveals that areas with low hydraulic conductivity, poor aquifer protective capacity, and moderate vulnerability exhibit elevated concentrations of heavy metals, turbidity, and contaminants. This result concludes that leachate infiltration significantly affects groundwater quality in these areas, underscoring the importance of our research. Hence, sanitary landfills should be located in areas with lower aquifer vulnerability, and strict waste management and monitoring practices should be implemented to prevent groundwater contamination. Effective management and monitoring strategies are essential to prevent structural compromise and further degradation of groundwater quality.

Keywords: Groundwater contamination, Leachate, Dumpsites, Vertical Electrical Sounding (VES), Groundwater

1. Introduction

Groundwater, a vital natural resource, plays an irreplaceable role in supporting all forms of life, particularly human existence. In Nigeria, groundwater contributes to approximately 80% of the domestic water supply in rural and emerging urban regions (National Groundwater Association, March 2012). Nonetheless, groundwater quality has steadily declined due to natural and human-induced activities. Over the past few decades, groundwater contamination has become a pressing concern within this study area (Agu et al., 2014). Among the multifaceted challenges faced by groundwater, the infiltration of leachate from solid waste disposal sites is a significant contributor. These dumpsites generate a contaminated liquid called leachate, which originates from decomposing waste materials within landfills, facilitated by rainwater infiltration through the waste matrix (Agu et al., 2014; Chian and Dewalle, 1976). Gradually, this leachate infiltrates the subsurface, eventually reaching the aquifer, compromising groundwater's suitability for human consumption and use (Kassenga&Mbluligwe, 2009). The improper disposal of waste on land has raised substantial concerns regarding its impacts on both surface water and groundwater resources, thereby prompting substantial research dedicated to assessing the effects of leachate infiltration into the groundwater within the confines of the study area (Okoye, 2020; Agu et al., 2014; Chiedozie et al., 2021; Andrea et al., 2012; Egbueri, 2018).

Amidst the voluminous body of literature addressing this issue within the study area, numerous factors, including topography, soil composition, aquifer characteristics, precipitation rates, and more, have collectively contributed to the incidence of leachate infiltration. Noteworthy contributions by (Zeng et al., 2021) make the undulating topographical features and soil type of the study area as prominent factors facilitating leachate infiltration into the groundwater more apparent. It is imperative to glean from research that the regional aquifer underlying the study area is situated at a considerable depth, approximately 500 meters below the surface (Nwajide, 1980; Nfor et al., 2007). Overlying this regional aquifer and outcropping to the surface lies the impermeable Imo Shale Formation, characterized by its imperfectly porous and permeable nature (Anyanwu &Arua, 1990; Nwajide, 1980; Nwajide, 2013; Ogbe &Osokpor, 2021). The formidable expense associated with drilling to access the regional aquifer has led to the utilization of some fractured or weathered parts of the Imo Shale Formation as an alternative source of shallow groundwater (Nfor et al., 2007; Emenaha et al., 2023). This formation comprises the Umunna and Ebenebe Sandstone members, manifested as discontinuous sandstone "tongues" within the Imo Formation (Nfor et al., 2007; Anyanwu &Arua, 1990; Nwajide, 2013). Additionally, where the shale is weathered or fractured, it serves as a groundwater source for indigenous communities at relatively shallow depths (20-60 meters) (Nfor et al., 2007). However, this shallow groundwater source is burdened by several inherent disadvantages. Seasonal variations exert significant control over groundwater availability. Due to its shallow disposition, it remains susceptible to contamination, both directly and indirectly, via leachate infiltration from surface dumpsites (Nfor et al., 2007).

In recent times, the research conducted by Chiedozie et al. (2020) delved into the impacts of solid waste deposition on soil quality and heavy metals within edible plants within a dumpsite in Awka. Their comprehensive investigation illuminated a disconcerting reality—namely, the substantial pollution of the surrounding environment attributable to the presence of heavy metals such as Lead, Mercury, Zinc, Cadmium, Chromium, Arsenic, Iron, Nickel, Cobalt, Selenium, Copper, stemming from non-sanitary waste disposal sites. Their findings revealed the hazardous implications of unlined dumpsites, which can potentially exacerbate environmental degradation with significant public health risks to the local inhabitants.

Furthermore, in a parallel study, Chiedozie et al. (2021) showed the examination of polycyclic aromatic hydrocarbons (PAHs) levels prevalent within leachates originating from an unlined dumpsite located in Agu-Awka, Anambra State. Their analysis unveiled a concerning revelation of leachates emanating from solid waste dumpsites harbor a complex mixture of organic and inorganic toxicants with elevated concentrations of PAHs. Acknowledging that these substances can contaminate groundwater and soil with high potency without protective lining materials necessitates serious attention and mitigation measures.

Furthermore, the increase in human population and commercial activities has engendered a substantial surge in domestic and industrial waste generation, presenting health challenges for the local population (Onyido et al., 2009; Chiedozie et al., 2021). The solubilized chemicals from waste decomposition persistently contaminate the groundwater (Andrea et al., 2012). In Agu-Awka, the presence of expansive dumpsites presents a cascade of detrimental consequences, including environmental pollution, severe deterioration in groundwater quality, high concentrations of heavy metals, and associated health-related concerns (Chiedozie et al., 2021; Nfor et al., 2007; Chiedozie et al., 2020; Umar et al., 2009).

Nevertheless, extant investigations into groundwater contamination within the study area tend to concentrate on isolated facets, often confining their scope to geotechnical, geochemical, or geophysical analyses, falling short of providing a holistic comprehension of the issue at hand. This study seeks to address this conspicuous research gap by adopting an integrated approach of geotechnical, geochemical, and geophysical methods, thus offering a comprehensive evaluation of the implications brought about by the infiltration of leachate into the groundwater system of the study area.

1.1. Study Area

The study area covers Agu-Awka and its surroundings, located within Awka City, the capital of Anambra State. Geographically, the study area falls between latitude 6° 13' 30" N to 6° 15' 0" N and longitude 7° 05' 30" E to 7° 07' 0" E, as shown in Figure 1. This area is in a valley near the Mamu River and sits about 300 meters above sea level.

In terms of climate, Awka experiences temperatures ranging from 27-30°C from June to December and 32-34°C from January to April (Omoja et al., 2021). The dry season, marked by intense heat, follows this pattern (Omoja et al., 2021). The area receives an annual rainfall between 1639.40mm and 3863.40mm, indicating a high likelihood of leachate infiltration and percolation (Omoja et al., 2021).

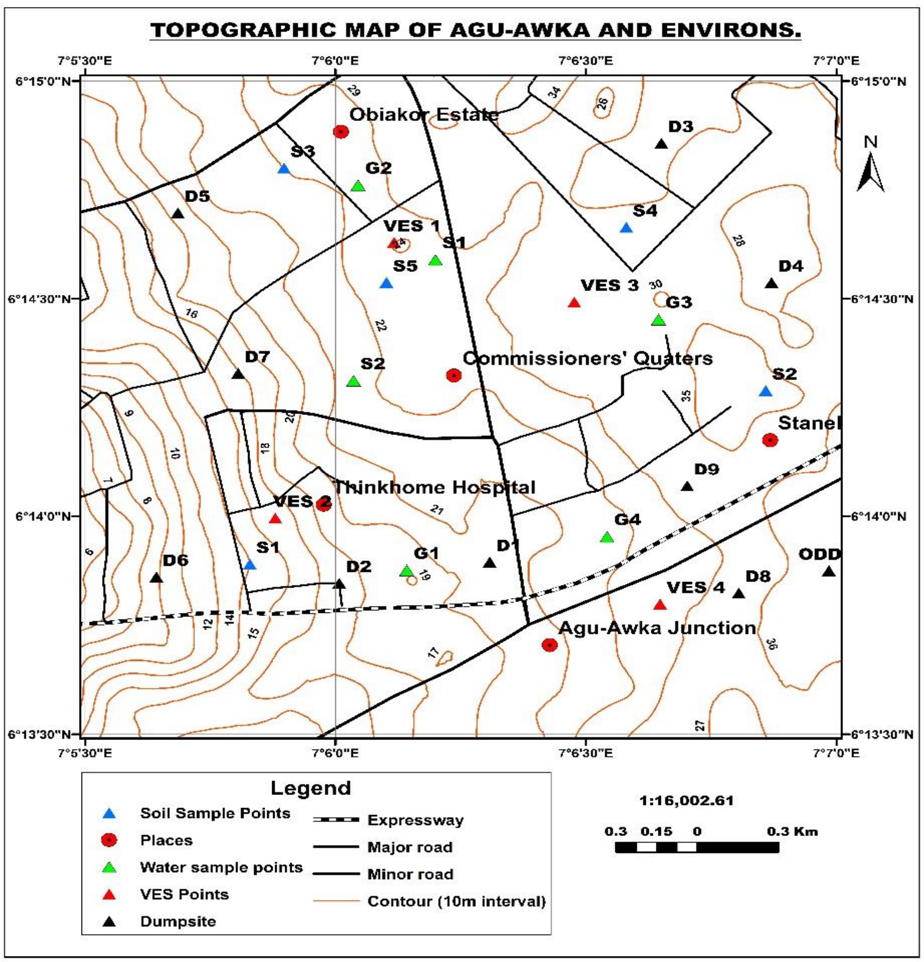

Fig. 1: Topographic map of the study area showing accessibility, places, and sample points.

The study area is located in the industrial heart of Awka, surrounded by markets, construction sites, industries, homes, and hospitals. These various establishments contribute different types of waste to the local dumpsite, which was not sanitarily managed during this study (Chiedozie et al., 2021). This mix of urban activities underscores the complexity of waste generation and its potential impact on groundwater contamination in the study area.

2.1 Geology of the Study Area

The Paleocene Imo Formation underlain the study area (Chinwuko et al., 2016; Nwajide, 2013), as depicted in Figure 2. This geological formation is the basal unit of the Niger Delta Basin (Nwajide, 2013; Nwajide, 1990; Ogbe &Osokpor, 2021). It extends southward in a concave pattern, stretching from the western Benin Flank, which overlays the Nsukka Formation of the Anambra Basin and widens as it moves eastward (Nwajide, 1990).

The thickness of the Imo Formation varies across the region. In the type area, it measures around 490 meters (Dessauvagie, 1975; Nwajide, 2013; Rayment, 1965), while in other outcropping regions, it can reach up to 1000 meters (Rayment, 1965). This geological formation is characterized by three prominent lithofacies components known as the Ebenebe, Igbaku, and Umunna Members (Anyanwu &Arua, 1990; Rayment, 1965; Nwajide, 2013; Nwajide, 1990). These members manifest as elevated ridges flanked by low-lying, marshy areas underlain by shales.

The sandstone members within the Imo Formation exhibit characteristics such as a coarse to fine-grained texture, heterolithic composition, flat-bedded structure, and an upward thickening pattern, which suggests their deposition in an inner shelf environment (Nwajide, 2013; Anyanwu &Arua, 1990; Nwajide, 1980). These rock layers have distinct boundaries where they meet, striking in a north-northwest to south-southeast direction and dipping to the south-southwest with an average dip angle of approximately 3 degrees (Anyanwu &Arua, 1990; Nwajide, 2013).

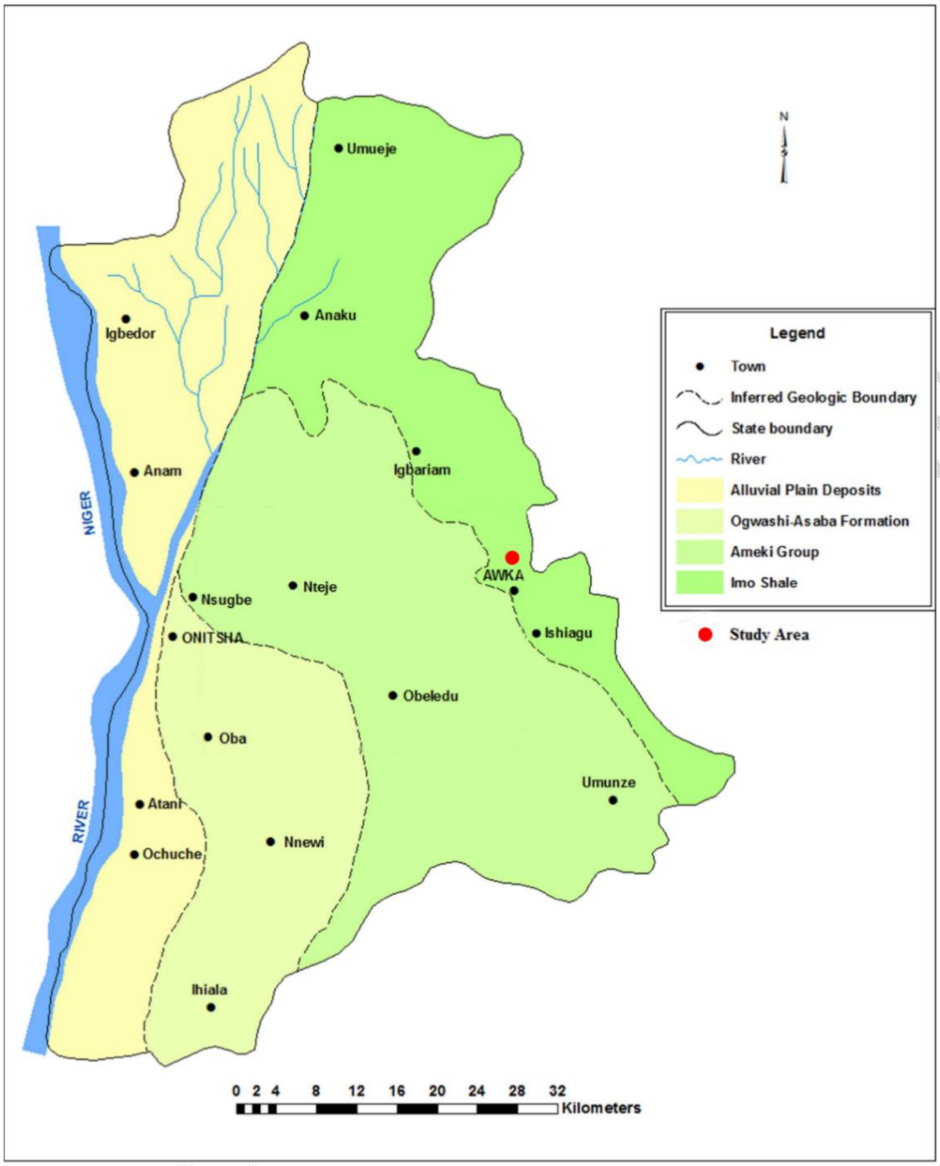

Fig. 2: Geologic map of Anambra state showing the study area (after Chinwuko et al, 2016)

2.2 Hydrogeology of the Study Area

Awka is hydrogeological configured into a multi-aquifer system due to the underlying Imo Formation (Nwozor et al., 2015) (Fig. 2). Low-permeability mudstones dominate the Imo Formation and constitute an aquitard (Nganje et al., 2017). In places where there are outcrops of sandy units, such as the Umunna Sandstone and Ebenebe Sandstone members, the Imo Formation may be seen as local confinements for the aquifers. In such areas, aquifer depths are usually 20 m to 60 m, with the uncertainty of their capacity to yield water in satisfactory quantities (Nfor et al., 2007; Emenaha et al., 2023). Consequently, the aquifer systems can be classified into shallow, unconfined, and deep confined aquifers.

2.2.1 Shallow Unconfined Aquifers

This first and topmost groundwater unit is recharged directly by precipitation and base flow infiltration. The shallow, unconfined aquifers occur in the shale units of the Imo Formation, which have been weathered by physical, chemical, and biological processes, thus giving the shale units the rare capacity to store and release water (Nfor et al., 2007). Also, outcrops of Ameki/Nanka Sands occur in some parts of Awka, constituting shallow unconfined aquifers with depth to exploitable groundwater ranging from 75m to 350m (Nfor et al., 2007). In the study area, the unconfined aquifer system is typically less than 20m - 60m deep (Nfor et al., 2007) and is considered shallow unconfined aquifers. The water table is very close to the ground surface and is controlled by seasonal variation (Nfor et al., 2007; Emenaha et al., 2023). Generally, the groundwater potential of this system is low and may sustain only small and discontinuous abstraction (Nfor et al., 2007; Emenaha et al., 2023; Nwajide, 2013; Nwankwoala et al., 2014).

2.2.2 Deep Confined Aquifers

The deep confined aquifer systems occur as local aquifer confinements in areas with outcrops of sandy units such as the Umunna Sandstone and Ebenebe Sandstone. Ajali Sandstone can be penetrated at about 500 m beneath the Imo Shale in some areas and constitutes the deep aquifer system that is capable of sustainable water production (Nfor et al., 2007; Nwajide, 2013; Nwajide, 1990; Nwajide, 1980). A borehole and geoelectric survey data show that the depth to the deep confined aquifer systems ranges from 180 m to 540 m (Nfor et al., 2007; Nwozor et al., 2015; Okoro et al., 2010).

2.3 Geochemistry of the Study Area.

The groundwater chemistry in a given area is a complex interplay of multiple factors, including the weathering of rock minerals, climatic conditions, redox reactions, geological and hydrogeological configurations, and human activities (Andrea et al., 2012). These elements collectively shape the composition and quality of groundwater resources in a region.

Based on the empirical findings presented by Egbueri (2018), the groundwater within the study area generally complies with established quality standards, with most physicochemical parameters falling within acceptable limits. However, notable observations include deviations in pH levels, categorizing the water as mildly acidic to neutral.

Furthermore, Egbueri (2018) identified the presence of heavy metals in the groundwater of the study area. These heavy metals are believed to originate from the nearby dumpsites, as Okoye (2020) noted. In terms of the dominant cations and anions in the groundwater of Awka, the order is as follows: Calcium (Ca) >Magnesium (Mg) >Sodium (Na) >Potassium (K) for cations, and Chloride (Cl) >Sulfate (SO_4) >Nitrate (NO_3) >Phosphate (PO_3) for anions, based on physicochemical analyses of water samples (Egbueri, 2018). Notably, heavy metals in Awka follow a particular hierarchy, with lead (Pb) being the predominant contaminant (Egbueri, 2018). Lead contamination is particularly concerning due to its adverse health effects, especially in elevated concentrations.

Egbueri (2018) also introduced a pollution index that ranges from 0.542 to 73.083 for the study area. This index indicates that the groundwater in the region may not meet the necessary quality standards for drinking purposes, suggesting potential health risks associated with its consumption. However, it could still be suitable for various domestic and industrial uses, emphasizing the importance of understanding the specific water quality requirements for different purposes.

In summary, the geochemical characteristics of groundwater in the study area reveal a detailed picture of water quality, reflecting a balance between meeting certain standards and presenting challenges related to pH levels and heavy metal contamination. These findings underscore the need for thorough assessment and vigilant management of groundwater resources to ensure their safety and suitability for various uses.

3. Methodology

The study employed a multidisciplinary approach, integrating geotechnical, geochemical, and geophysical methods to investigate and characterize the impacts of leachate infiltration from dumpsites in the groundwater system of Agu-Awka, south-eastern Nigeria.

The initial phase of this research involved conducting a desk study by reviewing published journals, articles, and books to gain a comprehensive understanding of the study area. Following the desk study, a reconnaissance survey was conducted to gather preliminary information before the actual field sample collection and acquisition. Five soil, six groundwater, and surface water samples were collected during the field studies at distributed locations in the study area. Four Vertical Electrical Sounding (VES) data were acquired following the Schlumberger array approach at distributed locations. The acquired samples were then processed and analyzed thus;

3.1. Geotechnical studies:

The geotechnical aspect of this research involved analyzing the Particle Size Distribution (PSD) and determining soil permeability using Hazen's equation. The collected soil samples underwent laboratory analysis to assess their Particle Size Distribution following procedures outlined in BS 1377 (1990). This test involved sieving the samples through different mesh sizes to determine the proportions of gravel, sand, silt, and clay. The PSD results provided insights into the soil composition and hydraulic behavior. Soil permeability was determined using Hazen's (1892) equation, which relates the permeability coefficient (k) to the grain size distribution. The soil permeability was calculated by applying Hazen's equation to the observed PSD data.

$$\boldsymbol{K} = \mathbf{C(D_{10})^2} \text{(Hazen,1892)}$$

Where k = permeability (cm/sec), C = Hazen's coefficient = 0.8 – 1.2 (typical = 1); D10 = effective particle size (mm).

Geophysical survey: The geophysical survey (Four points) utilized the resistivity method, precisely the Vertical Electrical Sounding (VES) technique. The VES data were acquired using an earth resistivity meter (ABEM SAS 1000 Terameter) with the Schlumberger array configuration (Fig. 3). The maximum half-current electrode spacing (AB/2) was set at 250m.

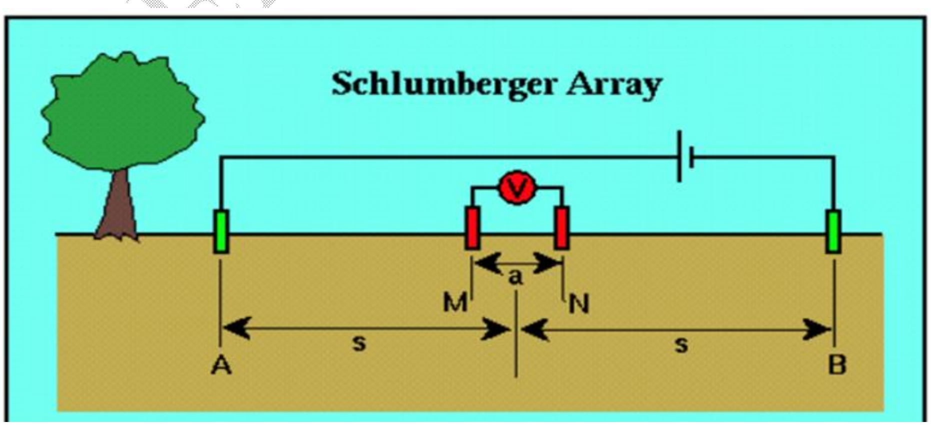

Fig. 3: Illustration of Schlumberger array (after Oyeyemi et al., 2022)

This technique involved the injection of direct or low-frequency alternating current into the ground through current electrodes (AB) and measuring the resulting voltage drop using potential electrodes (MN). The VES method was chosen due to its ability to visualize the vertical layers of the Earth's lithology. Based on these measurements, the apparent resistivity of the subsurface layers was calculated thus;

$$\rho_a = \frac{\Delta V}{I} K$$

Where ρ_a = Apparent resistivity

I = current

K = Geometric factor

Δv = potential difference across the potential electrodes.

The acquired resistivity data was analyzed using Interpex software. To assess the Aquifer Protective Capacity (APC), the longitudinal conductance (S) was calculated by multiplying the individual aquifer thickness (h_i) and resistivity (ρ_i). These conductance values were then compared to predefined standards by Henriet (1976), Oladapo et al. (2004), and Ogungbemi et al. (2013) (Table 1) to evaluate the protective capacity. An APC map was generated by plotting the longitudinal conductance values and samples' coordinates.

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$$

Table 1: Longitudinal Conductance/Aquifer Protective Capacity Ratings (after Henriet,1976; Oladapo et al., 2004 and Ogungbemi et al., 2013).

Longitudinal Conductance (mhos)	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

The DRASTIC Index model was employed to estimate aquifer vulnerability. Input factors such as resistivity survey data, geological field survey data, topographic and soil maps, and annual rainfall data were weighted (w) and rated (r) according to Navulur& Engel (1998) (Table 2). These factors were then applied to the DRASTIC model's empirical equation to compute the DRASTIC Index (DI) distribution.

DRASTIC Index (vulnerability rating) = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw

Where: D = Depth-to-water table, R = Net recharge, A = Aquifer media, S = Soil media, T = Topography, I = Impact of vadose zone, C = Hydraulic conductivity.

The DI values were used to infer aquifer vulnerability by comparing it to Navulur& Engel's (1998) standard. A vulnerability map was created by mapping the spatial distribution of the DI values.

Table 2: DRASTIC Index ranges for Aquifer Vulnerability (after Navulur& Engel (1998))

Hydraulic Resistance (Years)	Log (c)	Vulnerability level
0 – 10	<1	Very high
10 – 100	1-2	High
100 – 1000	2-3	Moderate
1000- 10000	3-4	Low
>10000	>4	Very Low

To interpret the geoelectric sections obtained from VES models to understand the subsurface lithologies, a chart (Fig. 4) showing the electrical conductivity and resistivity of common rocks byPalacky (1987) was used. The chart was used to interpret the layers of the rocks (sandstone, shale, or claystone) as recorded through their signature or responses to the current sent into the subsurface.

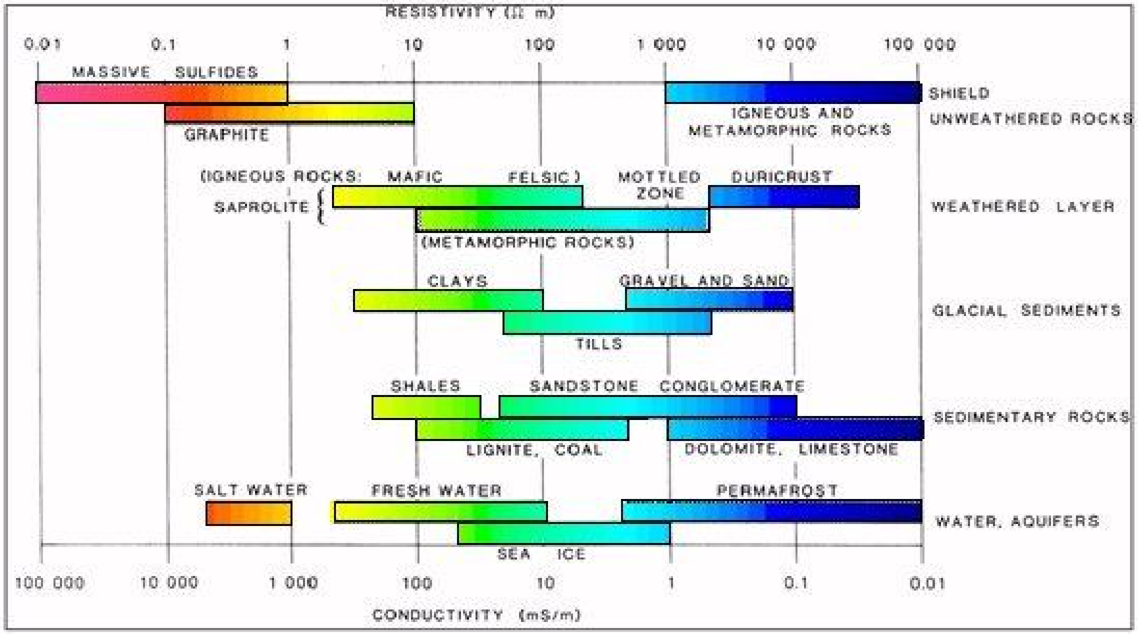

Fig. 4: Electrical conductivity and resistivity of common rocks (Palacky, 1987).

3.2. Hydrogeochemical study:

Six water samples from both ground and surface waters were collected within the study area for physiochemical analysis to complement the VES results. Two boreholes, two hand-dug wells, and two surface waters were selected for this study. The samples were collected in a small plastic bottle of one (1) liter capacity, rinsed with distilled water, and sent to the laboratory for immediate analysis. Samples were analyzed for the following parameters: pH, Temperature, Electrical Conductivity, Hardness, Turbidity, BOD, COD, Sulphate, Chlorides, heavy metals, and trace elements using standard methods described in APHA (1998). The analysis used the Atomic Absorption Spectrometry (AAS) method to identify and quantify various chemical and physical parameters in the study area. The water samples were examined for major ions such as Sulphate, Chlorides, Magnesium, Calcium, Potassium, and Sodium. Heavy metals, including Iron, Copper, Lead, Mercury, Chromium, and Argon, were also analyzed. Physical parameters such as temperature, electrical conductivity, hardness, BOD, and COD were also measured. Chemical laboratory analysis was conducted using an Atomic Absorption Spectrometer, while appropriate instruments were used to measure the physical properties. Summary statistics, including mean, mode, and range, were calculated for the concentration of each parameter and compared to the permissible limits for drinking water established by WHO (2007).

4. Results and Discussion

4.1 Geotechnics results and discussion

Figure 5 illustrates the graphical representation of the analyzed samples, providing insights into their grain size distribution. The samples exhibit diverse particle sizes, ranging from clay and silts to medium sands. As per the Unified Soil Classification System (USCS), these samples are classified as "poorly graded" soils. An in-depth analysis of Figure 5 yielded specific values for D10, D30, and D60, which served as key parameters in determining the coefficient of uniformity, coefficient of curvature, and estimated hydraulic conductivity. The study area's soil characteristics and hydraulic behavior findings are summarized comprehensively in Table 2, offering valuable information about the study area's soil characteristics and hydraulic behavior.

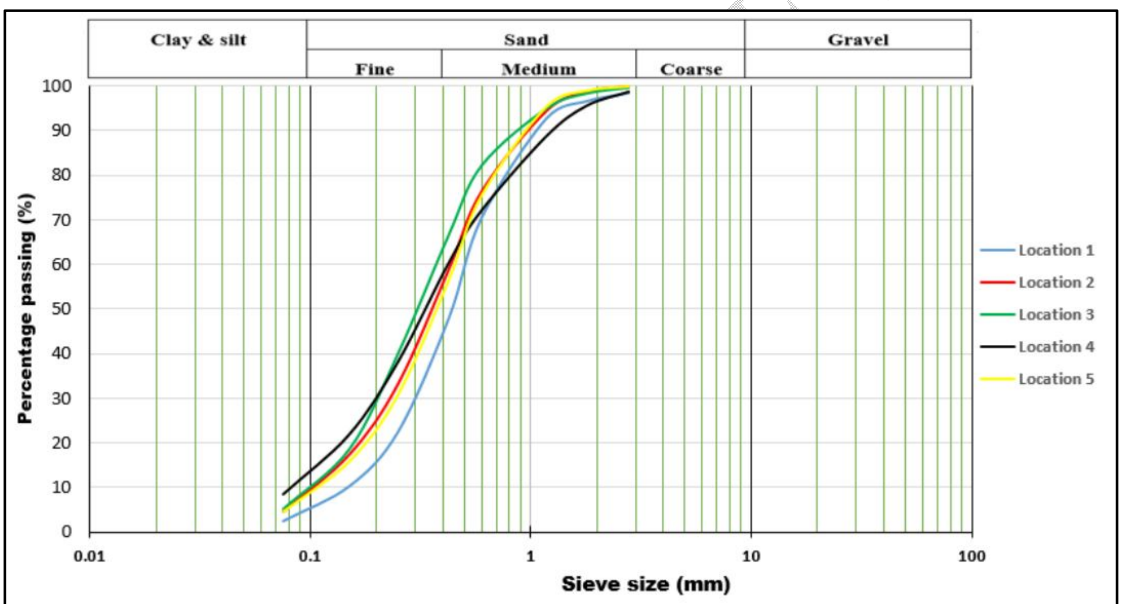

Fig 5: Particle size distribution curve of all samples collected from the study area.

Soil Sample	Longitude	Latitude	D10 (mm)	D30 (mm)	D60 (mm)	Cu	Cc	K (cm/sec)	Gradation
S1	7° 5' 49.8" E	6° 13' 53.3" E	0.148	0.302	0.519	3.501	1.187	0.022	Poorly graded
S2	7° 6' 51.2" E	6° 14' 17.4" E	0.107	0.230	0.436	4.084	1.133	0.011	Poorly graded
S3	7° 5' 53.5" E	6° 14' 47.9" E	0.102	0.203	0.381	3.728	1.060	0.010	Poorly graded
S4	7° 6' 34.8" E	6° 14' 39.9" E	0.084	0.200	0.419	4.998	1.137	0.007	Poorly graded
S5	7° 6' 5.9" E	6° 14' 32.4" E	0.110	0.244	0.458	4.142	1.181	0.012	Poorly graded

Table 3: Estimated hydraulic conductivity and soil sample gradation size.

Table 2 shows that location 1 and location 4 have the highest and lowest estimated values of hydraulic conductivity, respectively, with an observed trend that shows that: location 1 > location 5 > location 2 > location 3 > location 4. Hydraulic conductivity is a complex property that depends upon the sizes and shapes of interconnection between particles in a soil mass. However, the infiltration of fluids is controlled by the sizes and shapes of these interconnections. According to (Cabalar & Akbulut, 2016), poorly or uniformly graded soils are more have larger pore spaces and interconnections than well-graded soil. This is because, in the matrix of a well-graded soil, all soil sizes are present (fines to gravels) and the presence of the fines occupies the pores of the soil matrix reducing the pore spaces and the interconnectivity. The resultant effect is the reduction in the rate atwhich the soil transmits water and other fluids, hence low hydraulic conductivity. However, from the results of the grain size distribution test (Table 3), all soil samples collected in the study area are poorly or uniformly graded. The results of the analysis revealed that the area is primarily composed of friable, fine to medium-grained sand and weathered shale topsoil with estimated hydraulic conductivity ranging from 0.007 to 0.022 cm/s (Table 3) at depths of up to one meter. This result implies that there is a high tendency of the soils to easily transmit water and other fluids through them.

4.2 Geophysical survey results and discussion

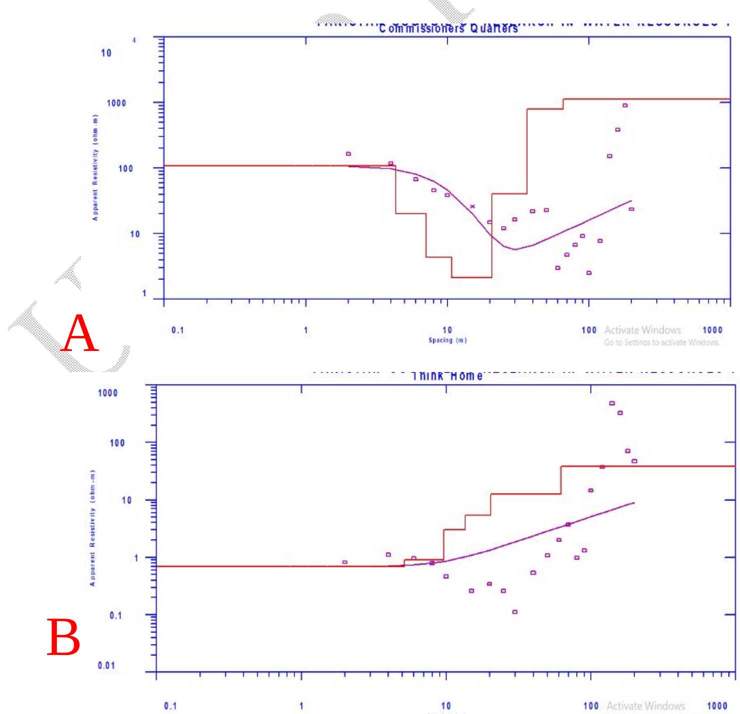

Fig. 6. Representative geo-electric curves within the study area. **A**= Commissioner quarters and **B**= Think Home Hospital.

Table 4:Summary of VES data points.

Layer	**App. Res. (Ω-m)**	**Thickness (m)**	**Depth (m)**	**Description**	**Longitude**	**Latitude**	**Elevation (m)**
VES 1: Ester Obiakor Estate					7°6'6.8"E	6° 14' 38" N	55
1	9.02	0.68	0.57	Topsoil			
2	119.67	2.67	4.02	Sandstone			
3	501.47	11.29	15.31	Water saturated sandstone			
4	6373.8	-	Base not reached	Sandstone			
VES 2: Think Home Hospital					7° 5' 52.9" E	6° 13' 59" N	63.7
1	0.79	9.25	7.35	Topsoil			
2	3.03	3.87	13.49	Shale			
3	5.41	6.78	20.27	Shale			
4	12.60	41.71	61.98	Shale			
5	38.34	-	Base not reached	Shale			
VES 3: Commissioner quarters					7° 6' 28.4"E	6° 14' 29.7" N	75.2
1	108.51	4.32	4.32	Topsoil (Sandstone)			
2	16.82	32.31	36.63	Shale			
3	788.70	28.88	65.51	Water saturated sandstone			
4	1125.80	-	Base not reached	Sandstone			
VES 4: Stanel					7° 6' 39"E	6° 13' 47.6" N	54.3
1	6373.8	0.58	0.58	Topsoil			
2	1183	1.35	3.31	Sandstone			

3	4.65	1.59	3.53	Shale	
4	5.59	23.92	77.59	Shale	
5	126.9	-	Base not reached	Sandstone	

4.2.1. Geoelectric Section Interpretation

The geophysical analysis revealed the presence of four to five geoelectric layers (Table 5) in the study area, predominantly composed of shale and sandstone vadose layers. Among these layers, the sandstones and weathered/fractured shale were identified as the primary water-bearing layers, occurring at an average depth of 55.01m. The aquiferous layers exhibited an average thickness of 26.45 meters, resistivity of 327.09 Ωm, and transmissivity of 143.44 m^2/day.

Table 5:Summary of geoelectric section interpretation.

VES point	**No. Of layers**	**Aquifer layer/unit**	**Aquifer thickness (m)**	**Aquifer depth (m)**	**Aquifer resistivity** (Ωm)	**Vadose zone**
Ester Obiakor Estate	4	Sandstone	11.29	15.31	501.47	Sandstone
Think-home Hospital	5	Shale	41.71	61.98	12.6	Shale
Commissioner Quarters	4	Sandstone	28.88	65.51	788.70	Shale
Stanel	5	Shale	23.92	77.59	5.59	Shale

4.2.2 Aquifer Protective Capacity Interpretation

The rating results, as presented in Table 6, showed that the study area is generally characterized by poor to suitable Aquifer Protective Capacity, which has implications for aquifer vulnerability.

APC map of the study area was produced from plotting the values of the longitudinal conductance and represented by a map in Figure 7.

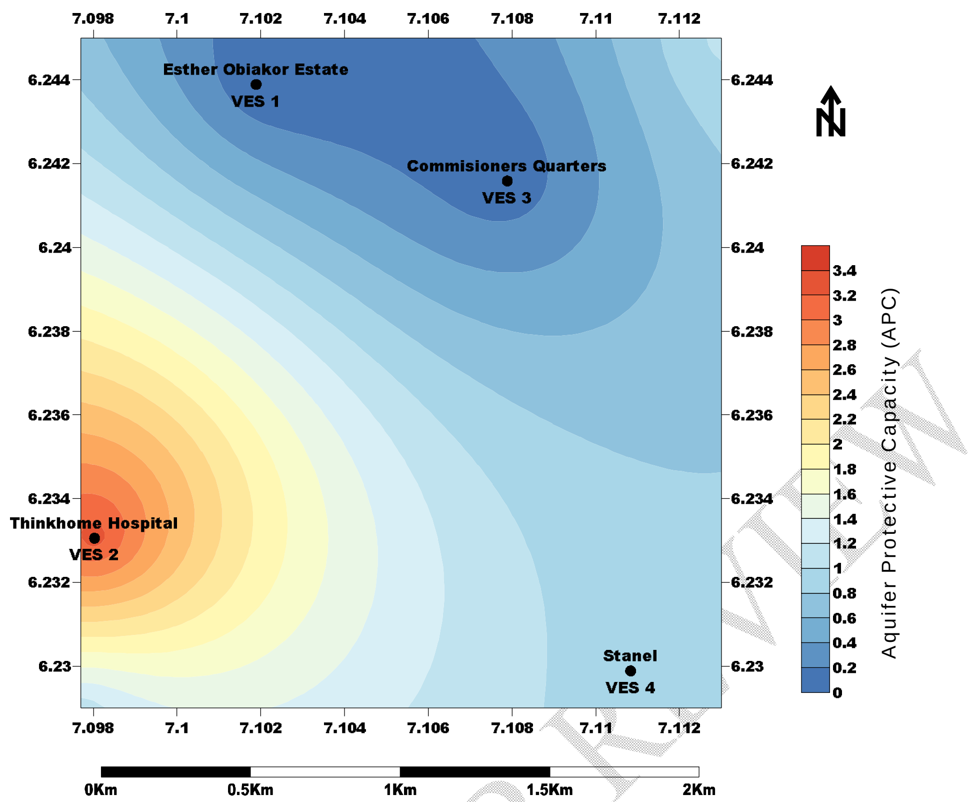

Fig. 7: Aquifer Protective Capacity of the study area.

4.2.3 Aquifer Vulnerability Index

Applying input factors to the DRASTIC model, the study area exhibited low to moderate vulnerability to contamination (Table 7). Overall, these findings imply that although the aquifer system in the study area shows a range of protective capacities, the vulnerability to contamination is not excessively high. Figure 8 shows the aquifer vulnerability map of the study area.

Table 7: Calculated DRASTIC Index and DRASTIC Qualitative Category of the sounding

VES Number And Location	**D (5)**	**R (4)**	**A (3)**	**S (2)**	**T (1)**	**I (5)**	**C (3)**	**DI**	**DRASTIC Qualitative Category**
Esther Obiakor Estate	10	9	5	1	10	2	1	126	Moderate
Think Home Hospital	7	9	1	1	10	2	1	99	Low
Commissioners Quarters	5	9	5	8	10	2	1	115	Moderate
Opposite Stanel	7	9	1	10	10	2	6	132	Moderate

locations.

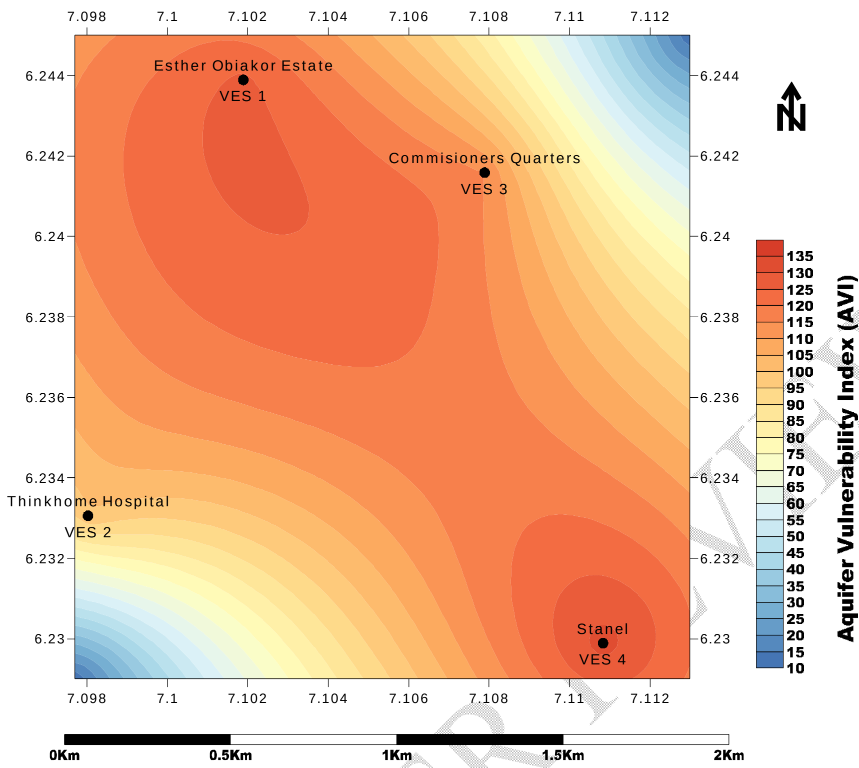

Fig. 8: Groundwater vulnerability map of the study area

4.3 Geochemical Results Interpretation

Table 8: Sample Locations and Coordinates

Sample Code	Location	Longitude	Longitude	Elevation
G1 (Borehole)	Think home Hospital	7° 6'8.9"E	6° 13' 52.5" N	82.37m
G2 (Borehole)	Commissioner Quarters	7° 6'2.8"E	6° 14'46" N	54.77m
G3 (Hand dug well)	Commissioner Quarters	7° 6'3.8"E	6° 14'27' N	62.24m
G4 (Hand dug well)	Opposite Stanel World Agu Awka	7° 6'32.6"E	6° 13'56.8" N	62.68m
S1 (Surface water)	Think home Hospital	7° 6'11.8"E	6° 14' 38" N	62.87m

S2 (Surface water)	Commissioner Quarters	7° 6' 1.6"E	6° 14'19" N	54.77m

a) Physical Parameters:

The analyzed physical parameters revealed unfavorable conditions for drinking water. The pH values in surface water and groundwater are slightly acidic (5.10 – 6.80) (Table 9). Although the turbidity levels for groundwater are below the maximum limit of 25 NTU recommended by WHO 2017, the turbidity levels are above the same standard in surface water (Table 9). However, all water samples observed an elevated BOD and COD level. High BOD levels can promote the growth of microorganisms such as bacteria, viruses, and protozoa in drinking water, leading to waterborne diseases such as cholera, dysentery, and gastroenteritis (Li & Liu, 2018). COD quantifies the amount of organics in water. The higher the COD value in drinking water, the more serious the pollution of organic matter (Davidson, 2001). According to Aralu et al. (2022) and Igboama et al. (2022), BOD and COD in groundwater have been associated with leachate infiltrations from uncontrolled dumpsites, sewage, and other anthropogenic activities.

Location	**pH**	**Temp**	**Electrical Conductivity (Us/cm)**	**Hardness (mg/L)**	**Turbidity (NTU)**	**BOD**	**COD**	**Sulphate**	**Chlorides**
G1	5.10	28.0	1.30	10	11.40	488	66.08	13.89	65
G2	6.60	28.0	1.40	88	13.10	128	52.48	14.17	72
G3	6.80	28.0	0.70	30	6.80	240	81.26	16.68	62
G4	6.20	28.1	0.50	40	8.90	312	23.68	16.25	90
S1	6.20	28.1	0.60	78	32.40	256	102.08	16.85	70
S2	6.40	28.0	0.60	80	64.60	104	90.88	21.55	63
WHO (2017)	6.5-8.5	-	1000	500	25	80	20	500	600
Min	5.10	28.0	0.50	10	6.80	104	23.68	13.89	62

Max	6.80	28.1	1.40	88	64.60	488	102.08	21.55	90
Mean	6.22	28.03	0.85	54.33	22.87	254.67	69.41	16.57	70.33

Table 9: Summary of levels of physical parameters in water samples.

b) Chemical Parameters

The concentrations of calcium, magnesium, sodium, and potassium within acceptable limits set by WHO 2017 for drinking water (Table 10), reveal the presence of essential minerals in the groundwater water of the area, contributing to its nutritional value.

The results of the heavy metal concentration in groundwater (Table 10) show that the Mercury concentration in both groundwater and surface water is the highest among the analyzed chemical parameters (0.040 – 0.253 mg/L). The elevated levels of mercury in the groundwater are primarily attributed to human activities, encompassing industrial discharges, household waste, unlawful waste disposal, and more. These findings corroborate the discoveries made by Egbueri (2018) and Andrea et al. (2012), both of whom documented heightened mercury concentrations in the study area's groundwater. However, prolonged exposure to high levels of Mercury has been associated with adverse effects on human health, including immune and digestive system disorders and potential damage to the liver, muscle weakness, vision loss, speech and hearing impairment, kidneys, and circulatory system (Obiri-Yeboah et al., 2021).

Similar trends were observed in Mercury concentrations, as Arsenic exceeded its WHO permissible limit for drinking water (Table 10). Contaminated water used for drinking, food preparation, and irrigation of food crops poses the greatest threat to public health from Arsenic (Ahmad & Bhattacharya, 2019; WHO Fact Sheet, 2022). Long-term exposure to Arsenic from drinking water and food can cause cancer and skin lesions (Parvez et al., 2011; WHO Fact Sheet, 2022). It is also associated with cardiovascular disease and diabetes (WHO Fact Sheet, 2022). In utero and early childhood, exposure has been linked to negative impacts on cognitive development and increased deaths in young adults (Ahmad & Bhattacharya, 2019; WHO Fact Sheet, 2022).

While most heavy metal concentrations are within acceptable limits by WHO for drinking water (Chromium, Lead, and Copper), their presence levels in the water samples can rise with continued exposure to the contamination sources, posing potential health risks. These observations suggest potential pollution of the groundwater source and emphasize the importance of continued monitoring and appropriate remedial actions to ensure the safety and quality of the groundwater resources.

Table 10: Heavy Metals and Trace Elements Analysis Results

Location	Fe (mg/L)	Cu (mg/L)	Pb (mg/L)	Hg (mg/L)	Mg (mg/L)	Cr (mg/L)	Na (mg/L)	Ar (mg/L)	Ca (mg/L)	K (mg/L)
G1	0.011	0.018	0.000	0.253	0.008	0.042	1.379	0.021	0.005	0.087
G2	0.000	0.003	0.000	0.046	0.013	0.000	3.248	0.006	0.162	1.016
G3	0.007	0.005	0.000	0.136	0.014	0.000	3.052	0.004	0.208	1.034
G4	0.009	0.000	0.000	0.040	0.021	0.321	3.200	0.026	0.182	0.716
S1	0.011	0.000	0.000	0.092	0.019	0.000	2.055	0.117	0.218	0.161
S2	0.009	0.000	0.010	0.059	0.018	0.000	2.885	0.014	0.115	0.518
WHO (2017)	0.3	2.0	0.01	0.006	150	0.05	50-60	0.01	75-200	20
Min	0.000	0.000	0.000	0.040	0.008	0.000	1.379	0.004	0.005	0.087
Max	0.011	0.005	0.010	0.253	0.021	0.321	3.248	0.026	0.218	1.034
Mean	0.007	0.004	0.001	0.104	0.015	0.061	2.637	0.031	0.148	0.589

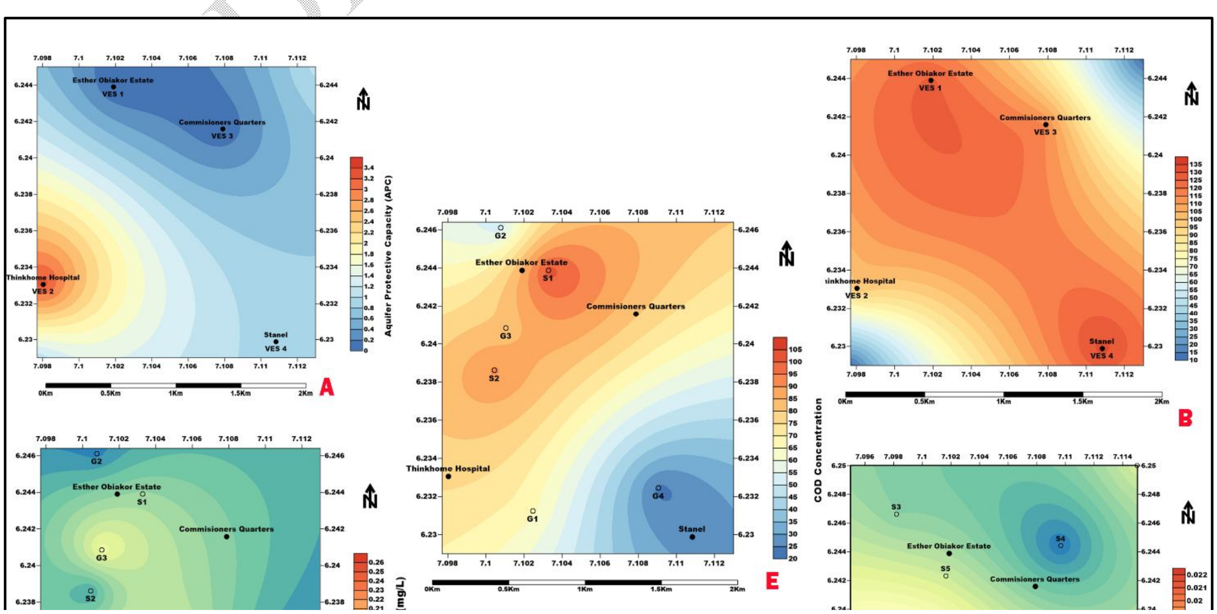

Fig. 9: Interpolated maps of the study area showing the relationship of the observed parameters.

A = Aquifer Protective Capacity map of the study area.

B = Groundwater vulnerability map of the study area

C = Mercury Concentration map of the study area

D = Soil hydraulic conductivity map of the study area

E = COD concentration map of the study area

Due to the elevated levels of heavy metals (Mercury and Arsenic), groundwater sources in the study area are unsuitable for human consumption. The surface water sources are also compromised by heavy metal content at levels higher than their permissible limits. In Figure 9, it was noticed that while heavy metals (Mercury and Arsenic) and COD levels in C and E, respectively, were higher in places with less permeable soil (D), the concentration of these contaminants was even worse in areas with many unplanned dumpsites and weak aquifer protection (A). This suggests that leachate infiltration is significantly affecting groundwater quality in these areas. However, there were discrepancies between the results of geophysics, which indicated shaley vadose layers, poor-to-good aquifer protection, and low-to-moderate vulnerability, and physicochemical analysis, which revealed the elevated concentration level of heavy metal contaminants in the study area. This discrepancy prompted a thorough review of existing hydrogeology, hydrogeochemistry, and geophysics literature in the study area. Previous studies by Nfor et al. (2007), Emenaha et al. (2023), Onyenweife et al. (2020), Agu et al. (2014), Nwozor et al. (2015), Nwajide (2013), Okoro et al. (2010) and Anakwuba et al. (2014) revealed that the study area consists of multiple aquifer systems which encompass shallow confined and perched aquifers, primarily attributed to the presence of the low-permeability Imo Formation, which acts as a confining layer for the Ajalli Formation – the regional aquifer situated at a depth of approximately 500m. Notably, the studies by Nfor et al.

(2007) and Emenaha et al. (2023) have documented the presence of shallow, thin, and discontinuous fingers or patches of Umunna and Ebenebe sandstone members within the impermeable Imo Formation. These sandstone units function as alternative groundwater sources due to cost considerations for accessing the deep-seated regional aquifer (Nfor et al., 2007). However, these alternative sources face challenges, including seasonal variations, contamination risks, and intermittent water supply (Nfor et al., 2007; Emenaha et al., 2023; Nwozor et al., 2015; Anakwuba et al., 2014).

This integrated study suggested that despite the favorable aquifer conditions observed in the geophysical survey results, leachates from unplanned dumpsites can easily contaminate the groundwater system through the fractured and weathered shaley vadose zone as conduits into the groundwater system. This is because the permeability abilities of fractured and weathered shale are similar to those of sandstone.

5. Conclusion

This study, utilizing an integrated approach, concludes that leachate infiltrations from unplanned dumpsites contribute to the degradation of the groundwater system in the area. The water quality evaluation raises significant concerns regarding heavy metal contamination in surface and groundwater samples. The exceeding concentrations of Chromium, Mercury, and Cadmium pose potential risks to human health and the environment. The contamination is likely attributed to anthropogenic sources, highlighting the urgent need for effective wastewater treatment, improved agricultural practices, and proper waste management.

Given the elevated levels of heavy metals, the surface water sources in the study area are polluted and unsuitable for direct consumption. Therefore, subjecting the water to treatment is imperative before it can be used for drinking. The study recommends using sanitary landfill technology for waste disposal to prevent groundwater contamination and its impacts. Strict waste management and monitoring practices should be implemented, including siting landfills and dumpsites in areas with good aquifer protective capacity and low vulnerability. Effective management and monitoring strategies are crucial to preserving groundwater quality and preventing further degradation. Addressing the heavy metal contamination is crucial for ensuring safe and clean drinking water for the local populace.

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