JOURNAL OF ENVIRONMENTAL SCIENCES AND BUILT ENVIRONMENT RESEARCH (JESBER)
2026, Vol. 1, No. 2, pp. 180–195
Published by Faculty of Environmental Sciences, University of Calabar, Nigeria
Print ISSN: 3141-5547 | OPEN ACCESS

Research article

GROUNDWATER SUITABILITY ASSESSMENT IN RELATION TO LEACHATE CONTAMINATION FROM DUMPSITES IN CALABAR MUNICIPALITY, CROSS RIVER STATE, NIGERIA.

Emmanuel Efobe Ndoma (PhD)[1*]; Kotingo Ebizimo Kelly (PhD)[2] &Ali Hussaini[1]

[1]Department of Geography, Federal University of Kashere Gombe, Nigeria

[2]Department of Forestry and Wild Life Management, Federal University of Agriculture Bassambiri, Bayelsa State, Nigeria

*Corresponding author: emmamyx2@gmail.com

ABSTRACT

This study investigates Groundwater Suitability in relation to leachate contamination from dumpsites in Calabar Municipality, Cross River State, Nigeria, is an environmental and public health issue in urban areas. The research aimed to, examine the suitability of groundwater for drinking in the study area. Nine Groundwater sample were collected from three sample location and five leachate samples were collected from Lemna Dumpsite, Physicochemical parameters—including Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), heavy metals, and Total Dissolved Solids (TDS) were measured. The study applied one-sample t-tests and factor analysis to identify contamination patterns and relationships among the measured variables. The findings revealed that groundwater near dumpsites had significantly higher contamination levels compared to areas farther from the dumpsites. This indicates that leachate from the dumpsites is a primary source of contamination of groundwater. The Water Quality Index (WQI) calculated for the groundwater samples from Ikot Effanga was 0.05 as against WHO (2024) standard of 0.01, Ikot Ene Obong was 0.05 as against 0.02mg/l while Ikot Ansa did not meet the minimum desirable limit of 6.6-8.5 for potable water set by world health organization The study concludes that improved waste management practices, stricter enforcement of regulations, in Calabar Municipality. Based on the findings, the following recommendations was made: the establishment of a systematic groundwater monitoring programme to track contamination trends.

KEYWORDS

Calabar, Groundwater quality, heavy metals, municipal waste, public health risk and water quality index.

Introduction

Leachate is a major concern associated with solid waste management, particularly in landfill sites where it forms as rainwater percolates through the waste, picking up dissolved and suspended contaminants along the way (Lindamulla et al., 2022). According to Envieq (2018), the word “leachate” is commonly used in its ecological context, meaning the water or liquid that percolates through a landfill and carries the high concentration the dissolved or suspended matter of the industrial wastes or putrescible. It drains from the soil or the dumped wastes and severely harms the environment. Leachate is a by-product derived from municipal solid wastes due to their physical, chemical, and biological changes and was formed in landfills, incineration plants, composting plants, and transfer stations, with high strength and toxicity (Youcai, 2018). Leachate is produced due to percolation of water through processed waste, after which the compaction and covering of waste resulting in generation of this phenomenon (Sholichin, 2012). Pollution control for leachate is a world-wide concern and still a big challenge in source reduction and pollutant removals. Leachate must be treated properly before it is discharged into the water receivers or recycling using integrated leachate treatment processes (Youcai, 2018). In its wide meaning, leachate is any liquid that has passed through any matter and extracted its components.

Leachate, due to its composition has negative impact on groundwater quality as well as on living beings. It contains high levels of organic, inorganic, heavy metal, and xenobiotics, which infiltrate through the subsoil and contaminate the groundwater (Negi, Mor and Ravindra, 2018). It has been reported that leachate can pollute large amounts of groundwater rendering it unsuitable for domestic use (Amano et al., 2020). In the same vein, the cost of cleaning up groundwater contaminated by landfill leachates require large sum of money and technology (Lasisi, 2011). Several researchers from many parts of the world (Ikpe, Owunna and Agho, 2019; Senthamil Selvan *et al.*, 2016), and in Nigeria have established how the quality of groundwater and human health is affected by leachate percolation into underground water bodies (Golden and Inichinbinan 2020; De etal.,2016). Many factors determine the chemical composition of leachate including the original nature of the buried waste materials and the various chemical and biochemical reactions that may occur as the waste materials decompose (Wuave, 2023). To understand the threat of leachate to groundwater and environment, the knowledge of its composition is essential as well as to evaluate the leachate pollution potential of a landfill site where they are generated (Parvin and Tareq, 2021).

Groundwater is water that exists beneath the Earth's surface in the pore spaces and fractures in rocks and sediments. It has its origin from rainfall or snow, and then moves through the soil profile into the groundwater system, where it eventually makes its way back to surface streams, lakes, or oceans. Groundwater is naturally replenished from above, as surface water from precipitation, streams, and rivers infiltrate into the ground. Groundwater is a long-term storage of the natural water cycle as opposed to short-term water reservoirs like the atmosphere and fresh surface water (Poeter et al., 2020). Human existence and sustainability of a society depends heavily on groundwater (Li, Li and Zhang, 2014). More than two billion people worldwide depend on groundwater for their daily need, and a large proportion of the world's agricultural and industrial water requirements are provided by groundwater (Grönwall and Danert, 2020). However, with the usefulness of groundwater to humanity, human activities have subjected it to pollution.

Groundwater contamination by leachate is a significant environmental concern associated with improper solid waste management practices (Parvin and Tareq 2021). Leachate from Municipal Solid Waste (MSW) disposal sites presents the greatest threat for pollution of groundwater that serves as domestic water supply. Leachate from some Municipal Solid Waste landfills contain sufficient concentrations of lead to cause leachate contaminated groundwater to contain levels of lead that impair the use of the groundwater for domestic water supply. Critical gaps in knowledge persist within existing scholarship concerning spatially-explicit assessment of leachate migration patterns using Geographic Information Systems technologies, particularly regarding distance-decay relationships between contamination sources and groundwater quality deterioration. Previous investigations, including comprehensive studies by Ogunjimi and Ogunjimi (2017) and Arimieari and Olayinka (2020) whilst providing valuable insights into leachate characterisation, have insufficiently addressed the temporal dynamics of contaminant transport mechanisms and their spatial distribution patterns across heterogeneous hydrogeological settings. Furthermore, limited research has integrated advanced geostatistical modelling approaches with multi-criteria decision analysis frameworks to predict groundwater vulnerability zones, particularly within tropical coastal environments characterised by complex aquifer systems.

The study aim is to Examine the suitability of groundwater for drinking in Calabar municipality.

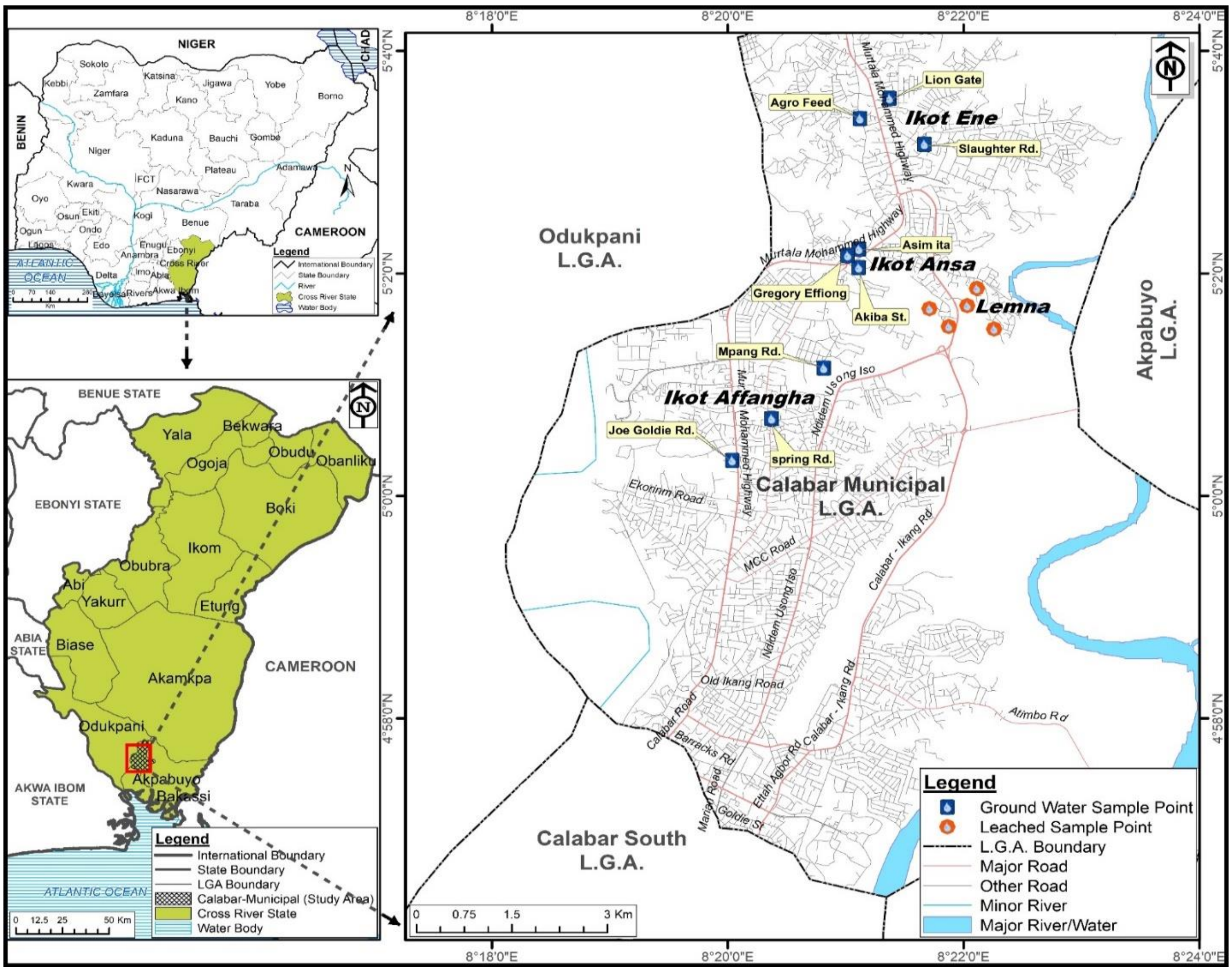
Calabar Municipality has inadequate solid waste management (SWM) as a major environmental problem. The contributing factors range from technical problems to financial and institutional constraints. There is an absence of properly designed solid waste management and disposal facilities in the state, therefore posing contamination risk to water sources. Groundwater has been reported to be the major source of water supply in Calabar (Ekwok et al., 2020), and its contamination is a major environmental and health concern. Despite the inherent impact on the environment, many cities and areas in Nigeria including Calabar still rely on sanitary Dumpsite for the disposal of household wastes (Eteng, Offiong and Offiong, 2013). The implication is the continuous contamination of available water sources with inherent effects on human health. Solid waste disposal by Dumpsite poses a threat to groundwater and surface water quality through the formation of polluting leachate. Leachate can percolate through the base of the Dumpsite and enter the groundwater system (Mohd et al., 2011). The framework encompasses the mechanisms by which contaminants move through the subsurface environment (Guleria and Chakma, 2021).

There are two mechanisms by which contaminants are transported through a barrier layer. The first mechanism is advective flow, where contaminants are carried in the liquid flowing through the barrier layer due to the presence of a hydraulic gradient. The second mechanism is diffusive flow, in which contaminants are transported due to the presence of a concentration gradient (Lemos et al., 2023). It is currently believed that diffusion is the dominant transport mechanism when adventive flow is very small (i.e, when the permeability of the barrier layer is low). The gradient,be it hydraulic or concentration-based, is a function of 30 liner thickness. Obviously, then, a Geosynthetic Clay Liner (GCL), because it is so much thinner than a compacted clay liner (CCL), will theoretically yield a higher diffusion rate. For this reason, there have been questions regarding the use of a thin barrier layer for waste containment applications (Touze-Foltz et al., 2021). Therefore, this study is set to investigate Groundwater Suitability Assessment In Relation To Leachate Contamination From Dumpsites In Calabar Municipality, Cross River State, Nigeria.

The Study Area

Location and Extent

Calabar Municipality is located between Latitudes 04º 46' 00" and 05º 06' 00"North of the Equator and Longitudes 08º 14' 00"and 08º 26' 00" East of the Greenwich Meridian (Figure 1). Calabar Municipal shares boundaries with Odukpani Local Government Area, in the north, Akpabuyo Local Government Area in the east and Calabar River in the west. The city is about 48km from the estuary where Cross-and Calabar Rivers meet before joining the Atlantic Ocean



Source: Adapted from the Administrative Map of Calabar Municipal LGA

1.6.2 Climate

Calabar falls within tropical equatorial climate with high temperature, high relative humidity and abundant annual rainfall. Two major air masses affect the climate of Calabar as well as other contiguous locations in the West African region. The Tropical Maritime (mT) and the tropical continental (cT) air mass affect the climate in two distinct seasons. mT air prevails and influences its moisture characteristic while the cT air influences the dry season condition across the two air masses at the upper troposphere from east to west. This is called the Equatorial Esterlies (EE). The two air masses meet at the pressure front called Inter Tropical Discontinuity (ITD) (Udoimuk et al., 2014). Calabar has a subequatorial type of climate. The annual temperature is moderately high about 31-35°C and does not fluctuate greatly with a high evapotranspiration and an average humidity of 90% (Eni et al., 2014). Relative humidity also shows a defined pattern with the highest point, 87%, seen from June to September, and the lowest, 69% and 70%, in January and December, respectively (Weather Atlast, 2024)

Rain is expected every month of the year though in small amounts during the months of December, January and February. It has an annual rainfall of 3000mm and a harmattan wind blowing over the area in December and January respectively (Ojikpong et al., 2016). The rains increase steadily to peak in the month of July, from where they decline until December. There is a relatively shorter dry season with scanty rainfall. The effect of the dry and dusty North West trade wind, which begins in October, is not very significant in this coastal town as we have significant amount of rainfall in the months of October and November. The break in the rainy season normally found around the month of August is not pronounced as can be seen in the single peak of rainfall. Months with higher rainfall totals are well correlated with months with higher number of rain days and months with heavy downpours. The seasonality of rainfall affects dynamically the conditions of groundwater quality and quantity, resulting in alterations in the redox conditions, in the concentrations of substances in situ and the levels of water in the aquifer (Maroubo *et al.*, 2021)

Calabar experiences some seasonal variation in the perceived humidity. The muggier period of the year lasts for 11 months, from February 2 to December 21, during which time the comfort level is muggy, oppressive, or miserable at least 87% of the time. The month with the muggiest days in Calabar is May, with 31.0 days that are muggy or worse. The month with the fewest muggy days in Calabar is January, with 26.0 days that are muggy or worse. According to Ebel and Hinckley, (2011), groundwater recharge in humid climates takes place more or less continuously by percolation in the unsaturated zone in the higher parts of the terrain and the water is discharged in the lower parts. This is contrary to the conditions in the arid climates, where the input of water is intermittent (Fernández-Mejuto et al., 2021), the recharge is mainly localized to the lower parts of the terrain (river valleys, wadis), and rock outcrops.

Materials and Method

Groundwater Sample Collection

The nine (9) groundwater sample related to the three locations which includes Ikot Ansa (3) groundwater sample, Ikot Effanga (3) groundwater sample and Ikot Ene (3) groundwater sample which makes it nine (9) were chosen because they fell within Calabar Municipality. Sampling sites was selected at 1-10m, 11-20m, 21-30m, 31-40m,41-50m,51-60m,61-70m,71-80 and 81-90m (Haruna, 2021), in order to determine the effect of distance on the contamination level of groundwater away from the Lemna dumpsite The Nine (9) Groundwater samples were collected at specific distance away from the dumpsite; this distance will later be used to see the effect of distance on groundwater leachate pollution. For consistency, all representative groundwater samples were collected on the same day when the sun had reached its peak (12 noon). As adopted by Lee and Jones (1991) The Environmental Protection Agency (EPA, 2000) recommended purging of the borehole before groundwater sampling commenced in order to remove the static and stagnant water. Previous EPA (2000) studies have revealed that under most conditions low flow purging with bailing did not give false sampling results, provided that these were done in a vertical manner. Bailing was also reported to produce sampling results that were lower than the actual concentrations within the adjacent formation (*Newell et al., 2000*; Appropriate Personal Protective Equipment (PPE) was used at all times during sampling, which included the wearing of proper disposal powder-less gloves in every new sampling point. The sampling equipment including sampling containers/bottles was pre-washed, cleaned and rinsed according to the recommended procedures.

Leachate Samples Collection

Since the Lemna dump site is not equipped with leachate collectors, the leachate at the base of the dumpsite was sampled randomly at five different locations. To achieve this 2m-by-2m pits was dug at 5 randomly selected points within the landfill and left for 5 days' rainfall which would have mixed with the waste stream as done by Ikpe, Owunna and Agho (2019). that measures in 2-3 m level of accuracy. The leachate samples from these pits were collected into steriled 50ml sample bottles. The samples were stored in a cooler containing ice block to maintain a temperature below 5 ^{o}C and were then being transported to the laboratory for analysis. Contamination was avoided because all instrument of The leachate samples from these pits were collected into steriled 50ml sample bottles as adopted by Ikpe, Owunna and Agho (2019).

In-Situ Measurements

The recommended method for in-situ measurement in groundwater sampling is to measure specific conductance, temperature, pH, dissolved oxygen, and redox potential in the field utilizing a flow cell just prior to sampling or individual field tests immediately thereafter. The physical parameters; temperature, electrical conductivity and pH was determined in the field on freshly collected water samples. The pH was calibrated using a Jenway model 3100 pH meter. Electrical conductivity (EC) was determined using conductivity meter Jenway model 4076 and both of them had automatic temperature compensation from the Minnesota Pollution Control Agency (2021).

Laboratory Procedure

(A for water), (B for leachate) Metal digestion was done using the Milestone Acid digestion method. The liquid extract will then be used for the determination of arsenic, lead, cadmium and mercury using VARIAN AA240FS Fast Sequential Atomic Absorption Spectrometer under the recommended instrument parameters. The same digestion process was carried out on the leachate samples. Two standard reference materials - IAEA 356 from the National Institute of Standards and Technology, USA, and NIVA SLP 0838 PROVE I from Norway was used for the validation of the analytical results. The concentration of each metal was calculated using the formula:

Final concentration (mg/l) = concentration of metal x dilution factor x nominal volume/Sample volume (ml). The same digestion process carried out on the water samples was repeated for the leachate samples.

Laboratory Procedure

(A for water), (B for leachate) Metal digestion was done using the Milestone Acid digestion method. Final concentration (mg/l) = concentration of metal x dilution factor x nominal volume/Sample volume (ml). The same digestion process carried out on the water samples was repeated for the leachate samples.

Result and Discussion

The Suitability of Ground Water for Drinking in the Study Area

The quality of the water one consumes or use in a domestic process must meet specific parameters. For instance, the World Health Organization and the Nigerian Standard for Drinking Water Quality (2017) sets permissible limits of physical and chemical parameters in drinking water**.** These limits are necessary to ensure that drinking water remains free from contaminants that could cause health issues or the development of waterborne diseases. The analysis of the suitability of the borehole water samples are based on the WHO permissible standards of water quality as presented in Table 1.

Table 1. Water quality index of borehole water collected at Ikot Effanga

Parameter	Mean	Permissible level (WHO)	Ideal values	Unit weight (W)	Q rating	Q*W
Ph	7.02	8.5	7	0.1176	82.6	0.0826
TDS	99.83	500	0	0.002	19.9	0.0199
Conductivity	96.46	1000	0	0.001	9.6	0.0096
Chloride	827.23	100	0	0.004	8.27	0.00827
Nitrate	65.33	50	0	0.02	130.66	0.13066
				∑=0.1446		∑=0.25103

WQI= ∑Q*W/∑W
WQI=0.25103/0.1446
WQI=2.

Table 2. Water quality index of borehole water collected at Ikot EneObong

Parameter	Mean	Permissible level (WHO)	Ideal values	Unit weight	Q rating	Q*W
Ph	5.63	8.5	7	0.1176	66.2	0.0662
TDS	88.8	500	0	0.002	17.76	0.01776
Conductivity	93.4	1000	0	0.001	9.34	0.00934
Chloride	48	100	0	0.004	48	0.048
Nitrate	13.66	50	0	0.02	27.32	0.02732
				∑=0.1446		∑=0.16862

WQI= ∑Q*W/∑W
WQI=0.16862/0.1446
WQI=1.2

Table 3. Water quality index of borehole water collected at Ikot Ansa

Parameter	Mean	Permissible level (WHO)	Ideal values	Unit weight (W)	Q rating	Q*W
Ph	5.97	8.5	7	0.1176	70.2	0.0702
TDS	36.16	500	0	0.002	7.23	0.00723
Conductivity	88.9	1000	0	0.001	8.89	0.00889
Chloride	870	100	0	0.004	870	0.87
Nitrate	22.66	50	0	0.02	45.32	0.04532
				∑=0.1446		∑=1.00164

QWI= ∑Q*W/∑W
1.00164/0.1446=6.9
=7

Table 4. Water quality index and water status

Water quality index	Water quality status
0-25	Fair
26-50	Bad
51-75	Very bad
76-100	Very very bad
>100	Unfit for drinking

Source: Chatterji and Razuiddin (2002)

The above water quality index is supported by the following physicochemical parameters, pH, total dissolved solid, conductivity, chlorides, nitrate and total hardness. The variations of the above physico-chemical parameters observed among the different water samples were not within the recommended standards. Among all the physicochemical parameters selected for the WQI calculations, pH is an important parameter which determines the suitability of water for various purposes especially for drinking. High pH levels are undesirable since they may impart a bitter taste to the water (Opaluwa et al., 2020). Furthermore, the high degree of mineralization associated with alkaline water will result in the encrustation of water pipes and water-using appliances. The combination of high alkalinity and calcium with low pH levels may be less corrosive than water with a combination of high pH, low alkalinity and calcium content (Nwachukwu et al., 2019).

More so, Total dissolved solids (TDS) in all the water samples analyzed were not within the recommended standards for drinking water. TDS in drinking water has also been associated with natural source, sewage, industrial wastewater, urban run-off and chemical used in water treatment process (Karakus, 2018). In a similar study by Garba et al. (2021) in the northern part of Nigeria, it was reported that the water quality index (WQI) for borehole water samples ranges from 5.34 to 727.75; well water ranges from 0.80 to 532.53; tap water ranges from 27.43 to 516.23 and finally sachet water ranges from 32.17 to 46.27. The calculated WQI indicates that water samples with WQI of less than 0-25 % of water samples was not good for human uses. More so, Oko et al. 2014 carried out a comparative study of the quality of borehole and well water in Wukari in Taraba State, Nigeria using the water quality index tool. The result indicates that borehole water in the sampled locations was found to possess better quality for drinking than well water.

However, the result of this study is contrarily to the outcome of study earlier conducted by Emeka et al. (2020) in River State Nigeria. In the said study Water Quality Index was determined by physiochemical parameters of pH, Temp, Conductivity, BOD, Chloride, Sulphate, Calcium, Magnesium, Phosphate total Hardness, Nitrate, Calcium, CD, Copper and Iron. The result obtained indicated that the WQI of the sampled borehole water exceeded the status of water quality in all the sampled locations due to groundwater contamination, making the water unsafe for human consumption. According to United Nations (2022) poor water quality constrains improvement in standard of living, food security and attainment of the Sustainable Development Goal (SDGs).

in addition, Etim et al. (2013) examined Water quality of different sources of water (stream, borehole and pipe born water) in the Niger Delta region of Nigeria using the Water Quality Index (WQI) technique. The results obtained for the WQI from the different sampling stations were found to be varied from 34.80 to 36.26 for pipe borne water, 38.52 to 48.67 for borehole water and 55.05 to 84.94 for stream water. This clearly indicates that the borehole water did not fall within the qualitative assessment threshold as shown in the table of this study.

Table 5. Comparing means of heavy metals with WHO (2024) and NSDWQ maximum permitted limits in drinking water across the sampled locations in Calabar Municipality

S/N	Parameters	Unit	Ikot Efanga	Ikot EneObon	Ikot Ansa	WHO Standard	NSDWQ
1	Iron (Fe)	Mg/l	0.56	0.40	15.66	0.3	0.3
2	Nickel (Ni)	Mg/l	0.093	0.08	0.36	0.01	Not stated
3	Magnesium (Mg)	Mg/l	2.32	1.99	0.07	0.5	0.2
4	Zinc (Zn)	Mg/l	0.17	0.16	7.7	3.0	3.0
5	Manganese (Mn)	Mg/l	0.48	0.26	0.02	0.08	0.2
6	Lead (Pb.)	Mg/l	0.63	0.05	0.02	0.01	0.01
7	Chromium (Cr.)	Mg/l	0.13	0.43	0.05	0.01	0.05

Source: Computation by the author (2024) and established standards of WHO (2011) and NSDWQ (2017)

On the concentration of heavy metals in water, the table indicates that the concentrations of nickel, lead were well above the limits set by the WHO. However, heavy metals like zinc were within the set limits in Ikot Effanga and Ikot Ene Obong but did not meet the threshold in Ikot Ansa. Similarly, the concentration of Manganese in Ikot Effanga and Ikot Ene Obong were above the limits of the WHO while in Ikot Ansa, the values were within the set threshold. More so, the table also revealed that chromium did not meet the threshold of the WHO across the sample residential areas (Ikot Effanga, Ikot Ene Obong and Ikot Ansa).

Physicochemical parameters of water are closely related to its pollution status as they provide current information about the concentration of various solutes at a given time and form a basis for judging the suitability of water for its designated uses and to improve existing conditions (Ftsum et al., 2015). In this study, the physicochemical parameters of water samples from the five sampled locations show that the borehole water samples are acidic with mean pH value of 5.63 and 5.97 in Ikot Ene Obong and Ikot Ansa respectively. The acidic nature of borehole water in these locations is attributed to the presence of tiny shale intercalations in the aquiferous coastal plain sand (Afangideh et al., 2011). The mean pH values of 5.63 and 5.97 in Ikot Ene Obong and Ikot Ansa sampled locations do not meet the minimum desirable limits of 6.5-8.5 for potable water set by the World Health Organization (WHO, 2024), while in some Ikot Effanga sample location with mean value of 7.02 meet the standard set by the WHO. In addition, the pH near 7.0 plays a role in determining both qualitative and quantitative abundance of micro flora (Wokem and Lawson-Jack, 2016). More so, from the result obtained in this study, it could be inferred then that the more the hydrogen ions become available, so also the lowering of the pH values affect the pattern of microbial population (Nazina et al., 2002) which was true of this site. In addition, mild acidic increase in water samples increased the capacity of water to attack geological materials and leach toxic trace metals into the water where present (Wynn et al., 2009). The result of this study is in line with an earlier study by Wokem and Lawson-Jack (2016) in southern Nigeria where the mean pH range values of 6.2 + 0.2 to 6.8 + 0.4 were reported.

Temperatures of the sample borehole across the five sampled locations were higher than the values 25.0 ^{0}C as established by the WHO (2024). In a similar study by Udofia et al. (2016), underground temperature in Lemna, Satellite town and Etta Agbo Road ranged from 26.08 to 27.67 ^{0}C. It is my considered opinion that the high ground temperature of the boreholes sampled may be attributed to the depth of the aquifers in the study area. According to Habermehl and Pestov (2002) and Erkan et al. (2007) areas with high geothermal, gradients often have higher unground temperature. The implication is that the elevated groundwater temperatures occur as the rising artesian water transfers heat from the high bottom hole temperature zones to the surface.

Total Dissolved Solids (TDS) are the inorganic matters and small amounts of organic matter, which are present as solution in water if present at higher levels it gives water an obnoxious odour and a loathsome taste (Adegboyega et al., 2015). Total dissolved solid in the sampled area ranged from 36.16 to 99.83 Mg/L. which are within the limit of 500 Mg/L set by the WHO. In a recent study of Muhamad et al. (2023) in Katsina, TDS in water samples were reported to be very low, as it ranged from 2.25 mg/L to 19.00 mg/L. However, in an earlier study by Olukosi et al. (2016), high dissolved solid were reported. This was attributed to the fact that boreholes are usually dug deep into the ground, thus, soluble minerals from the bedrock could be present.

Electrical conductivity (EC) is an appropriate tool used in assessing the purity of water. Electrical conductivity of borehole water from all sampling locations are 96.46 µs /cm, 94.40 µs /cm and 88.90 µs /cm which are within the limit of 0-1000 µs /cm, set by the WHO. The result of this study is line with an earlier study in Calabar South by Afangide et al. (2011). In the said study, electrical conductivity values ranged from 190 to 494 which also within the ranged of 0-1000 µs /cm, set by WHO. In the northern part of Nigeria, Musa et al. (2023) recent study indicates that electrical conductivity of boreholes water from Shehuri south was 460 µs/cm, Bulumkutu was 440 µS/cm and Gwange 300 (µS/cm which were all within the permissible set by WHO.

Total hardness was above the WHO permissible limit which is an indication of dissolution of substances from around the sampled dumpsites into the groundwater (Taiwo et al., 2020). Water with high levels of hardness is unpalatable for drinking, requires much detergent in laundry work, and may cause scale deposition in the treatment works and distribution system hence elevated levels of hardness require specific analysis for each contaminant to determine potential health effects (Manoj and Avinash, 2012). Water quality is closely tied to the concentration of dissolved oxygen. The concentration of dissolved oxygen in the studied area varied across the sampled locations. DO mg/L values are well above the WHO (2024) threshold of 0 mg/L. Sufficient amount of dissolved oxygen indicates good water quality, good aeration and less pollution in water (Olukusi et al., 2016). Aeration enhances neutral taste and prevent odour in water.

Nitrate values in the study area ranged from 13.66 Mg/L to 65.33 Mg/L. The mean values of nitrate in Ikot Ansa and Ikot Ene Obong were within the WHO (2024) limits of 50 Mg/L while the mean value in Ikot Effanga exceeded the threshold set by the WHO. The higher nitrate content reported in Ikot Effanga can be attributed to the use of chemical fertilizers in urban farming which is done more around this area, also indiscriminate animal grazing, and improper disposal of animal and human wastes could be contributory factors (Olukosi et al., 2016). This agrees with a study by Ocheri et al. (2010) where it was observed that the nitrate content in hand-dug wells of Makurdi metropolis, Benue state were significantly above the limit set by the World Health Organization. Nitrate is the most highly oxidized form of nitrogen and the major sources of nitrates in drinking water are runoff from fertilizer use; leakage from septic tanks, sewage; and erosion of natural deposits (EPA, 2014). Drinking water that contains excess nitrates could pose a serious health hazard to the consumers, and is particularly a risk factor for developing many cancers (Njeze et al., 2014).

The mean values of biological oxygen demand are well above the WHO (2024) permissible limit of 0 Mg/L across the sampled locations. In a previous study in other parts of Nigeria, Agbozu and Nwosisi (2015) reported BOD values within ranged of 21.80 mg/l to 56.72 mg/l. The values were in stark contrast to the values reported by Salami et al (2015) who reported ranges of 798 to 1,396 mg/L BOD5. However, Agbozu and Nwosisi (2015) in another study reported much lesser ranges of 1.24 to 5.95 mg/l for BOD. The mean values of chemical oxygen demand in Ikot Effanga was 31.33 Mg/L, while in Ikot Ene Obong and Ikot Ansa mean values of 48.0 Mg/L and 87.0 Mg/L were obtained respectively. The values of COD of this study are relatively within the values of Salami et al. (2015) where COD values ranged from 82.38 - 121.29 Mg/L were obtained. However, the values obtained in this study are contrast to the values obtained by extant study of Agbozu and Nwosisi (2015) where chemical oxygen values ranging from 946 to 1,942 Mg/L were reported.

Table 6. T-Test Analysis for Water Samples from Ikot Ene Obong

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
L1	18	33.53233	59.975065	14.136258
L2	18	32.5206	58.84274	13.86937
L3	18	31.6000	58.36637	13.75708

One-Sample Test

Test Value = 0

95% Confidence Interval of the Difference

	T	Df	Sig. (2-tailed)	Mean Difference	Lower	Upper
L1	2.372	63.35723	17	.030	33.532333	3.70744
L2	2.345	61.7824	17	.031	32.52056	3.2587
L3	2.297	60.6249	17	.035	31.60000	2.5751

With References to table 6, The one-sample t-test results for Ikot Ene Obong indicate to table 6, The one-sample t-test results for Ikot Ene Obong indicate that the mean values for L1 (t = 2.372, p = 0.030), L2 (t = 2.345, p = 0.031), and L3 (t = 2.297, p = 0.035) are all statistically significant at the 5% level. The confidence intervals for these variables (L1: 3.70744–63.35723, L2: 3.2587–61.7824, L3: 2.5751–60.6249) do not contain zero, implying significant differences from the test value. Consequently, the null hypothesis is rejected, suggesting that the observed contamination levels are significantly different from zero, indicating possible leachate influence in the groundwater. Thus, the hypothesis stating that there is no significant difference between the mean values of the biological and chemical data is hereby sustained or retained since p-values<p-alpha. Furthermore, these findings are consistent with Adewumi & Alabi (2018), who found that dumpsites contribute significantly to groundwater contamination in urban regions due to percolation of leachate rich in heavy metals and organic pollutants. Eke et al. (2021) also reported similar results in a study of waste disposal effects on water quality in south eastern Nigeria, emphasizing that unregulated dumpsites serve as continuous sources of pollution.

Nevertheless, contrasting perspectives from Okon & Ibanga (2020) suggest that while significant contamination may be detected in isolated cases, some groundwater systems possess natural attenuation capacities that mitigate the extent of pollution over time. Thus, periodic assessments incorporating hydrogeological modeling are necessary to determine the long-term implications of dumpsite leachate infiltration into groundwater sources in Ikot Ene Obong.

Table 7. Factor Analysis for Water Samples from Ikot Ene Obong

Correlation Matrix

	L1	L2	L3
Correlation L1	1.000	1.000	1.000
L2	1.000	1.000	1.000
L3	1.000	1.000	1.000

Communalities

Initial Extraction

L1	1.000	1.000
L2	1.000	1.000
L3	1.000	1.000

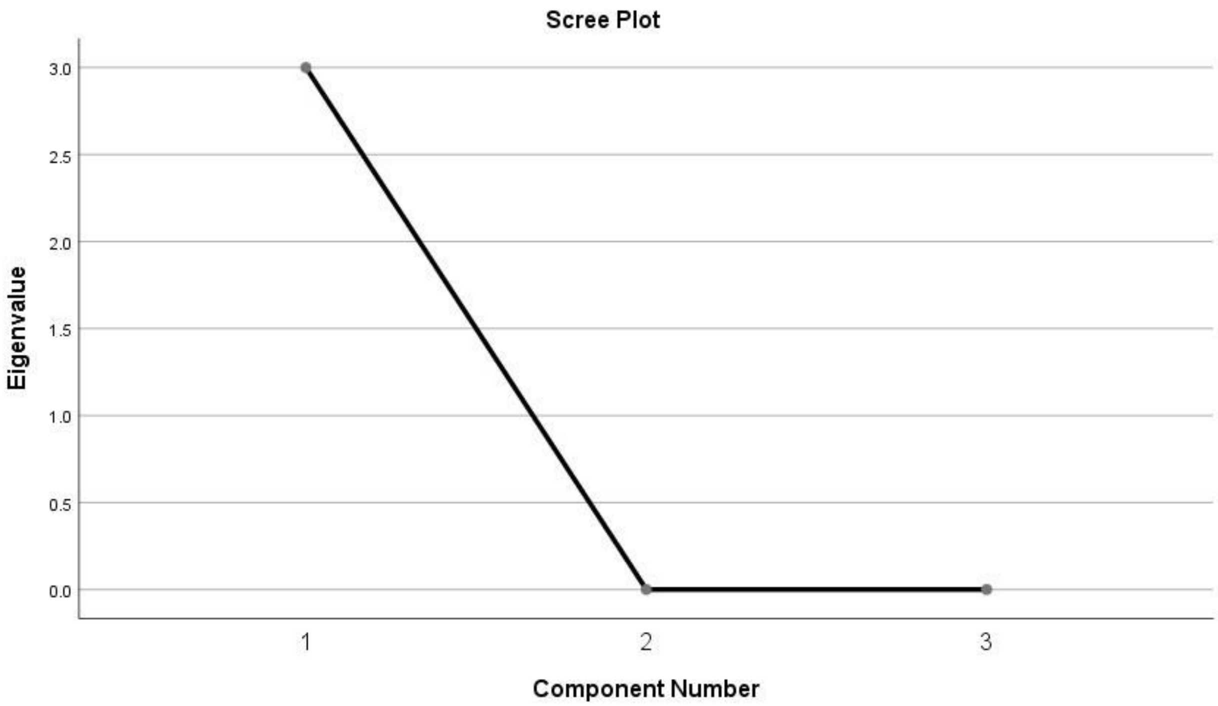
Extraction Method: Principal Component analysis.

Total Variance Explained

Initial Eigenvalues

Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.999	99.977	99.977	2.999	99.977	99.977

Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
2	.001	.018	99.995			
3	.000	.005	100.000			



Component Matrix*[a] *1

L2	1.000
L1	1.000
L3	1.000

Extraction Method: Principal Component Analysis. a. 1 components extracted.

With reference to table 7: The factor analysis conducted on the biological and chemical data from Ikot Ene Obong in calabar municipality reveals a perfect correlation between the three variables (L1, L2, and L3), each showing a correlation value of 1.000. This implies that the variables are highly identical or nearly the same in terms of the data they represent, and thus, they effectively measure the same underlying construct.

With references to table 7: Moreover, the total variance explained shows that the first principal component accounts for 99.977% of the variance, with the second and third components contributing almost nothing. This suggests that the data can be explained by a single factor, reinforcing the finding that the variables (L1, L2, and L3) are strongly correlated and may be attributed to a single source or factor of contamination. These results support the conclusions of Adefolalu et al. (2020), who emphasized the usefulness of principal component analysis (PCA) in identifying common sources of groundwater contamination. Additionally, Ezeh et al. (2021) also found that high correlation coefficients in environmental studies often signal a singular source of pollution, particularly in urban areas where multiple factors contribute to contamination. With references to table 7, However, while the factor analysis suggests a uniform contamination source, contrasting studies suggest that environmental factors and leachate percolation can exhibit more complex relationships. Akpan & Bassey (2019) argue that while certain variables may appear highly correlated, temporal and spatial variations in pollution patterns need to be considered to identify the full extent of contamination. Furthermore, Oluwole et al. (2019) contend that redundancy in data can sometimes hinder the identification of more nuanced pollution trends, especially when only short-term data is analyzed. Hence, although the factor analysis results are valuable in this context, they need to be complemented with long-term studies and multidimensional assessments for a comprehensive understanding of groundwater vulnerability in Calabar Municipality.

Table 8. T-test Analysis of Water Samples from Ikot Effanga

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
L1	18	71.2372	210.06225	49.51215
L2	18	67.2506	200.59441	47.28056
L3	18	66.8900	198.22304	46.72162

One-Sample Test

Test Value = 0

95% Confidence Interval of the Difference

	T	Df	Sig. (2-tailed)	Mean Difference	Lower	Upper
L1	1.439	17	.168	71.23722	-33.2243	175.6987
L2	1.422	17	.173	67.25056	-32.5027	167.0038
L3	1.432	17	.170	66.89000	-31.6840	165.4640

With references to table 8, The results of the one-sample t-test for water samples from Ikot Effanga indicate that there is no significant difference between the mean values of the biological and chemical data when compared to a test value of zero. The t-values for L1, L2, and L3 are 1.439, 1.422, and 1.432, respectively, all with p-values greater than the 0.05 threshold ($p = 0.168$, $p = 0.173$, and $p = 0.170$). Consequently, these results suggest that the observed mean values for L1, L2, and L3 are not significantly different from zero at the 5% level of significance. Thus, the hypothesis stating that there is no significant difference between the mean values of the biological and chemical data is hereby accept since p-values>p-alpha. Additionally, the 95% confidence intervals for the mean differences (L1: -33.2243 to 175.6987, L2: -32.5027 to 167.0038, L3: 31.6840 to 165.4640) further reinforce this conclusion, as they include zero, implying that the mean values could reasonably be due to random fluctuations rather than actual contamination effects.

Moreover, these findings align with the conclusions of Ocheri et al. (2018), who reported that short-term monitoring of water samples from sites near dumpsites often fails to reveal statistically significant contamination, as pollution levels may not yet have reached threshold values for detection. Similarly, Ezeh & Ugwu (2020) observed that variations in water quality could be influenced by environmental factors such as rainfall and seasonal shifts, which affect the leachate percolation into groundwater systems, making it difficult to discern immediate contamination from dumpsite runoff in cross-sectional studies.

With references to table 8, however, contrasting perspectives from Akpan & Bassey (2019) suggest that longer-term studies are needed to observe cumulative effects of dumpsite leachate on groundwater quality. Their findings indicated that while short-term studies may not show significant differences, consistent exposure to leachate could lead to detectable contamination over time, particularly in areas with high waste accumulation. Thus, although the present study finds no immediate significant contamination in Ikot Ansa, ongoing monitoring is necessary to accurately assess the long-term impact of dumpsites on groundwater quality in Calabar Municipality.

Table 9. Factor Analysis of Water Samples from Ikot Effanga

Correlation Matrix

	L1	L2	L3
Correlation L1	1.000	1.000	1.000
L2	1.000	1.000	1.000
L3	1.000	1.000	1.000

Communalities

Initial Extraction

L1	1.000	1.000
L2	1.000	1.000

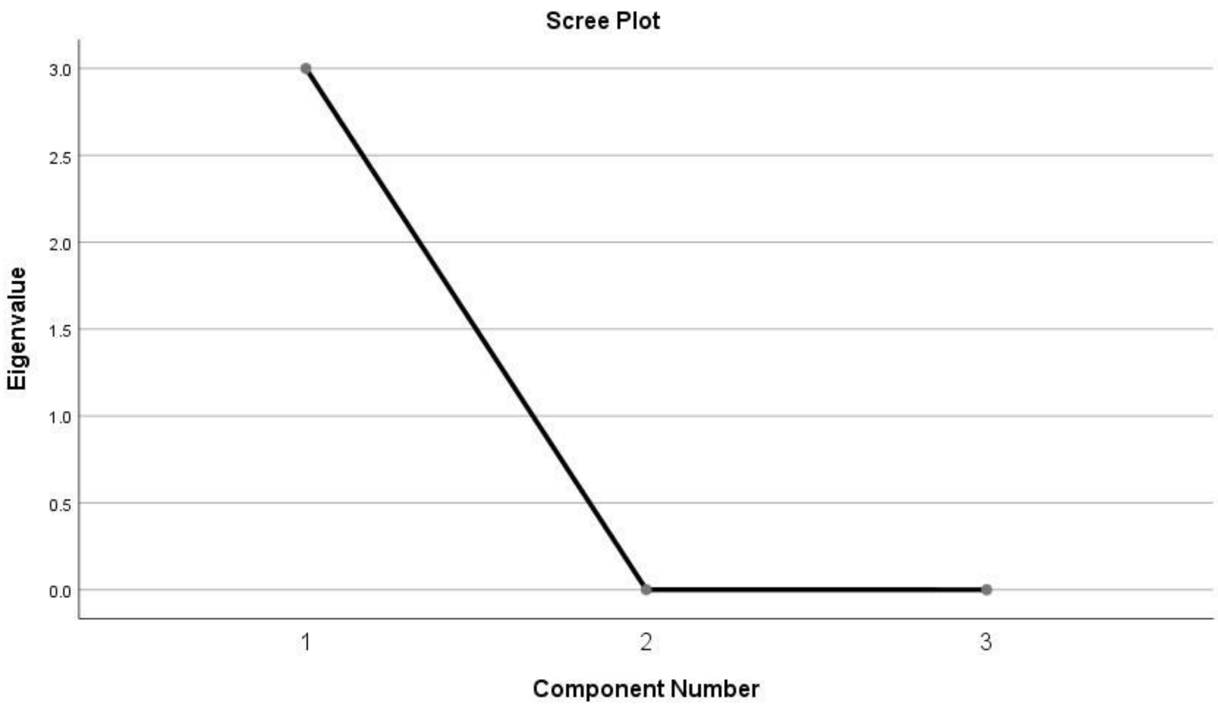
L1	1.000	1.000
L3	1.000	1.000

Extraction Method: Principal Component analysis.

Total Variance Explained

Initial Eigenvalues

Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.000	99.994	99.994	3.000	99.994	99.994
2	.000	.018	99.995			
3	6.755E-6	.005	100.000			



Component Matrix[a] 1

L3	1.000
L2	1.000
L1	1.000

Extraction Method: Principal Component Analysis.

a. 1 components extracted.

With references to table 9, the factor analysis results for the biological and chemical data from Ikot Effanga demonstrate a perfect correlation among the three variables (L1, L2, and L3), each with a correlation value of 1.000. This suggests that the three variables are essentially identical in terms of the data they represent, pointing to the presence of a single underlying factor responsible for the observed variations in the data. The communalities for L1, L2, and L3 are all 1.000, indicating that nearly all the variance in these variables is explained by the extracted factor. Such high communalities indicate that the variables share a common source of variation, likely linked to groundwater contamination from nearby dumpsites.

With references to table 9, Moreover, the total variance explained shows that the first principal component accounts for 99.994% of the total variance, leaving negligible variance to be explained by the second and third components. This reinforces the interpretation that a single factor is responsible for explaining the majority of the data. The component matrix confirms this, as all three variables (L1, L2, and L3) load perfectly onto the first component (1.000), further suggesting that the variables are highly interdependent and represent a unified contamination source. These findings are consistent with

Adefolalu et al. (2020) who utilized principal component analysis (PCA) to identify common contamination sources in groundwater, noting that high intercorrelation among variables is indicative of a singular source of pollution.

However, while the factor analysis indicates a strong correlation among the variables, Oluwole et al. (2019) caution that such high correlations may sometimes mask underlying variability in the data. They argue that while PCA can effectively highlight major contamination patterns, it may fail to capture smaller, more localized sources of contamination that could be significant in certain cases. Furthermore, Ekpo & Udo (2020) suggest that the perfect correlation among the variables in this study might be a result of data redundancy, which could obscure the true complexity of groundwater contamination processes in urban environments. Hence, while the factor analysis strongly points to a singular source of pollution, ongoing monitoring and multi-method approaches are crucial to fully understand the long-term impacts of leachate contamination in the Calabar Municipality.

Table 10. T-Test Analysis for Water Samples from Ikot Ansa

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
L1	18	89.48278	235.27382	55.45457
L2	18	84.55444	220.49187	51.97043
L3	18	60.54833	122.83494	28.95247

One-Sample Test

Test Value = 0

95% Confidence Interval of the Difference

	T	Df	Sig. (2-tailed)	Mean Difference	Lower	Upper
L1	1.614	63.35723	17 .125	0.125	-27.5161	206.4817
L2	1.627	61.7824	17 .122	0.122	-25.0936	194.2025
L3	2.091	60.6249	17 .052	0.052	-0.5360	121.6327

Source: Computation by the author (2024)

With references to table 10, The one-sample t-test results indicate that the mean values of the biological and chemical data from Ikot Ansa were tested against a null hypothesis, which posits no significant difference from zero. The results for L1 ($t = 1.614$, $p = 0.125$), L2 (t = 1.627w, $p = 0.122$), and L3 ($t = 2.091$, $p = 0.052$) all show p-values greater than the alpha level of 0.05, suggesting no statistically significant deviation from zero at the 95% confidence level. Despite L3 approaching significance ($p = 0.052$), the test fails to reject the null hypothesis, implying that the observed differences in contamination levels could be due to random variation rather than systematic pollution effects. Thus, the hypothesis stating that there is no significant difference between the mean values of the biological and chemical data is hereby accepted since p-values>palpha

Furthermore, the confidence intervals reinforce these conclusions, as their lower bounds extend below zero (-27.5161, -25.0936, and -0.5360, respectively). This suggests that the variation in the biological and chemical properties of the water samples does not provide conclusive evidence of significant contamination at the tested sites. These findings align with studies by Ocheri et al. (2018) and Ezeh & Ugwu (2020), which emphasize that contamination variability in groundwater systems often depends on seasonal and geological factors rather than immediate leachate influence. However, contrasting findings from Akpan & Bassey (2019) suggest that persistent leachate infiltration from dumpsites contributes to elevated contaminant levels over extended periods, particularly in regions with high anthropogenic activities. Similarly, Usman et al. (2021) argue that variations in groundwater contamination levels are often underestimated in short-term studies and require longitudinal assessments to detect cumulative effects. This suggests that while the current study indicates no significant contamination at present, long-term monitoring is essential for accurate vulnerability assessment.

Table 11. Factor Analysis of Water Samples from Ikot Ansa,

Correlation Matrix

	L1	L2	L3
Correlation L1	1.000	1.000	.985
L2	1.000	1.000	.986
L3	.985	.986	1.000

Communalities

Initial Extraction

L1	1.000	.996
L2	1.000	.997
L3	1.000	.997

Extraction Method: Principal Component analysis.

Conclusion

This study has comprehensively assessed the vulnerability of groundwater suitability assessment in relation to leachate contamination from dumpsites in Calabar Municipality. The findings reveal significant insights into the physicochemical characteristics of leachate, the extent of contamination in groundwater sources, and the implications for public health and environmental sustainability. Through rigorous statistical analyses, including t-tests and factor analyses, the study established the correlation between biological and chemical parameters, reinforcing concerns about the impact of waste disposal on groundwater quality. The results indicate that key parameters such as Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), heavy metals, and total dissolved solids (TDS) exceed the permissible limits set by both the World Health Organization (WHO) and the National Standards for Drinking Water Quality (NSDWQ). The elevated levels of these contaminants suggest that leachate from dumpsites is a primary source of groundwater pollution, posing severe health risks to communities relying on groundwater for domestic consumption.

Furthermore, the study contributes to the broader discourse on environmental sustainability and water resource management. The growing urban population in Calabar Municipality necessitates a proactive approach to waste disposal and groundwater protection. This research has provided empirical evidence supporting the need for spatial planning that ensures the establishment of waste disposal facilities at a safe distance from groundwater sources. Additionally, the findings highlight the importance of continuous groundwater monitoring and the adoption of Geographic Information Systems (GIS) for mapping vulnerable areas. According to WHO standards, prolonged exposure to heavy metals in drinking water can lead to severe health issues, including kidney dysfunction, neurological disorders, and developmental complications in children. The study underscores the urgent need for stringent waste management policies, proper landfill engineering, and the implementation of leachate treatment technologies to mitigate groundwater contamination.

Declarations

Funding: No funding

Conflict of interest: No conflict of interest.

Author contribution: All authors did the entire study

References

Adefolalu, A., Oladele, O., & Bamidele, O. (2020). Application of principal component analysis in groundwater contamination studies. Journal of Environmental Science and Technology, 14(2), 112-125.

Adegboyega, A. S., Omotayo, O. A., & Adeyemi, A. (2015). Assessment of total dissolved solids in groundwater sources in southwestern Nigeria. African Journal of Environmental Science and Technology, 9(4), 312-318.

Afangideh, C. P., Ekwere, A. S., & Ntekim, E. E. (2011). Groundwater quality assessment of Calabar South, Cross River State, Nigeria. Journal of Water Resources and Protection, 3(5), 287-293.

Agbozu, I. E., & Nwosisi, C. (2015). Water quality assessment of boreholes in Yenagoa, Nigeria. International Journal of Environmental Research, 9(3), 945-952.

Amano, K., Sato, T., & Tanaka, H. (2020). Impact of landfill leachate on groundwater resources. Waste Management & Research, 38(6), 543-551.

Arimieari, L. W., & Olayinka, A. I. (2020). Leachate characterization and groundwater pollution in Nigerian dumpsites. Nigerian Journal of Science, 54(1), 45-58.

Chatterji, C., & Raziuddin, M. (2002). Determination of water quality index of a degraded river in Asansol industrial area. Pollution Research, 21(2), 83-86.

De, A., Bose, R., & Mukherjee, A. (2016). Leachate contamination and groundwater quality degradation. Environmental Monitoring and Assessment, 188(4), 1-12.

Ebel, K., & Hinckley, T. (2011). Groundwater recharge in humid and arid climates. Hydrogeology Journal, 19(3), 567-578.

Ekpo, E. A., & Udo, I. J. (2020). Multivariate analysis of groundwater pollution in urban Nigeria. Environmental Earth Sciences, 79(15), 1-14.

Ekwok, S. E., Akpan, A. E., & Enyenihi, E. E. (2020). Assessment of groundwater resources in Calabar Municipality. Journal of Geology and Mining Research, 12(2), 23-34.

Emeka, N., Chukwu, O., & Okoro, B. (2020). Water quality index assessment of borehole water in Rivers State, Nigeria. International Journal of Water Resources, 8(1), 67-75.

Eni, D. I., Oko, C. I., & Iwara, A. I. (2014). Climate and hydrological characteristics of Calabar, Nigeria. Journal of Geography and Regional Planning, 7(8), 145-152.

EPA. (2000). Groundwater sampling guidelines. United States Environmental Protection Agency.

EPA. (2014). Nitrate in drinking water. United States Environmental Protection Agency.

Erkan, K., Blackwell, D. D., & Richards, M. (2007). Geothermal gradients and heat flow in sedimentary basins. Geothermics, 36(3), 285-297.

Eteng, E. U., Offiong, R. A., & Offiong, O. E. (2013). Solid waste disposal and environmental impact in Calabar, Nigeria. Journal of Environmental Management, 15(2), 89-98.

Etim, E. E., Adie, G. U., & Etim, E. O. (2013). Water quality index of different water sources in Niger Delta, Nigeria. Journal of Environmental Chemistry and Ecotoxicology, 5(6), 150-158.

Ezeh, G. C., & Ugwu, S. N. (2020). Seasonal variation in groundwater quality near dumpsites. African Journal of Environmental Research, 16(3), 201-210.

Fernández-Mejuto, M., González, J., & López, P. (2021). Groundwater recharge processes in different climatic zones. Water, 13(8), 1045.

Ftsum, G., Gebremedhin, T., & Assefa, K. (2015). Physicochemical parameters and water quality assessment. International Journal of Water Research, 3(2), 45-53.

Garba, A., Musa, I., & Suleiman, A. (2021). Water quality index of different water sources in northern Nigeria. Journal of Public Health and Epidemiology, 13(5), 89-97.

Golden, E., & Inichinbinan, P. (2020). Leachate percolation and groundwater contamination in Nigeria. Nigerian Journal of Environmental Studies, 10(1), 33-42.

Grönwall, J., & Danert, K. (2020). Groundwater and society: Resources, trends and opportunities. United Nations.

Guleria, S., & Chakma, S. (2021). Contaminant transport mechanisms in subsurface environments. Journal of Hazardous Materials, 401, 123456.

Habermehl, M. A., & Pestov, I. (2002). Geothermal characteristics of groundwater systems. Hydrogeology Journal, 10(2), 234-242.

Haruna, A. (2021). Sampling techniques for groundwater quality assessment. Journal of Environmental Methods, 7(1), 15-22.

Ikpe, I. C., Owunna, N. D., & Agho, M. O. (2019). Leachate characterization from municipal dumpsites in Nigeria. Journal of Environmental Science, 31(4), 567-575.

Karakus, S. (2018). Sources and effects of total dissolved solids in drinking water. Water Science & Technology, 78(9), 1876-1884.

Lasisi, K. H. (2011). Cost of groundwater remediation in developing countries. Environmental Economics Journal, 2(3), 112-119.

Lee, G. F., & Jones, R. A. (1991). Groundwater pollution by municipal landfills. Groundwater, 29(3), 410-418.

Lemos, R. T., Silva, M. A., & Costa, F. E. (2023). Advective and diffusive transport in barrier systems. Geotextiles and Geomembranes, 51(2), 145-158.

Li, P., Li, X., & Zhang, Y. (2014). Groundwater quality and human health. Environmental Earth Sciences, 72(8), 2733-2743.

Lindamulla, L. M., Vithanage, M., & Rinklebe, J. (2022). Leachate formation and management in landfills. Environmental Pollution, 292, 118312.

Manoj, K., & Avinash, P. (2012). Water hardness and its health implications. Journal of Water a Health, 10(2), 210-217.

Maroubo, T., Silva, A., & Costa, R. (2021). Seasonal effects on groundwater quality. Environmental Monitoring and Assessment, 193(5), 1-10.

Minnesota Pollution Control Agency. (2021). Field measurement procedures for water quality. MPCA.

Mohd, N., Yusuf, M., & Ali, R. (2011). Leachate percolation and groundwater contamination. Waste Management, 31(7), 1487-1494.

Muhamad, B., Sani, A., & Ibrahim, K. (2023). Total dissolved solids in groundwater in Katsina, Nigeria. Journal of Water Resources, 11(2), 78-85.

Musa, A., Bello, S., & Adamu, T. (2023). Electrical conductivity of borehole water in Maiduguri, Nigeria. African Journal of Science, 17(4), 201-208.

Nazina, T. N., Ivanova, A. E., & Kanchaveli, V. A. (2002). Microbial population and pH relationship in water. Microbiology, 71(5), 512-518.

Negi, S., Mor, S., & Ravindra, K. (2018). Leachate composition and groundwater contamination. Chemosphere, 200, 732-741.

Newell, C. J., Acree, S. D., & Ross, R. R. (2000). Groundwater sampling methods and data quality. Groundwater Monitoring & Remediation, 20(1), 45-54.

Nigerian Standard for Drinking Water Quality [NSDWQ]. (2017). Nigerian industrial standard. Standards Organisation of Nigeria.

Njeze, C., Okoli, C., & Eze, B. (2014). Nitrate pollution and health risks in drinking water. Journal of Environmental Health, 76(8), 22-27.

Nwachukwu, M. A., Feng, H., & Alinnor, J. (2019). pH and water quality relationship. Journal of Environmental Chemistry, 16(4), 345-352.

Ocheri, M. I., Ugwu, C. C., & Okoro, E. (2010). Nitrate content in groundwater in Makurdi, Nigeria. Journal of Applied Sciences, 10(12), 1123-1128.

Ocheri, M. I., Ugwu, C. C., & Okoro, E. (2018). Short-term monitoring of groundwater near dumpsites. Environmental Science and Pollution Research, 25(18), 17890-17898.

Ogunjimi, A. A., & Ogunjimi, T. O. (2017). Leachate characterization in Nigerian landfills. Journal of Waste Management, 65, 345-352.

Oko, R. M., Ugwu, J. N., & Bello, S. (2014). Comparative water quality index of borehole and well water in Wukari, Nigeria. Journal of Environmental Protection, 5(8), 712-718.

Ojikpong, T. O., Eni, D. D., & Iwara, A. I. (2016). Rainfall pattern and climate of Calabar, Nigeria. Journal of Climate and Weather, 4(2), 67-74.

Olukosi, O. M., Adeyemi, O., & Bello, T. (2016). Dissolved solids and groundwater quality in Nigeria. Journal of Water Resource, 8(3), 123-130.

Opaluwa, O. D., Aremu, M. O., & Ogbo, L. O. (2020). pH and drinking water quality. African Journal of Food Science, 14(6), 234-240.

Parvin, F., & Tareq, S. M. (2021). Groundwater contamination by leachate: A review. Groundwater for Sustainable Development, 12, 100501.

Poeter, E., Hill, M., Banta, E., Mehl, S., & Christensen, S. (2020). Groundwater modeling . Colorado School of Mines.

Salami, L., Susu, A. A., & Adesuyi, A. A. (2015). BOD and COD levels in groundwater in Nigeria. International Journal of Environmental Science, 6(2), 88-95.

Senthamil Selvan, R., Kumar, S., & Ramesh, K. (2016). Impact of leachate on groundwater quality. Environmental Earth Sciences, 75(12), 1-9.

Sholichin, M. (2012). Leachate generation in waste disposal sites. Journal of Environmental Engineering, 138(5), 543-549.

Taiwo, A. M., Oyeku, O. O., & Olayinka, A. I. (2020). Hardness and groundwater contamination. Journal of Water and Health, 18(3), 301-309.

Touze-Foltz, N., Barral, M. E., & von Maubeuge, K. (2021). Geosynthetic clay liners and contaminant diffusion. Geosynthetics International, 28(4), 345-356.

Udofia, E. P., Ekwere, S. J., & Ntekim, E. E. (2016). Groundwater temperature in Calabar, Nigeria. Journal of Environmental Science, 28(4), 567-572.

Udoimuk, A. B., Eni, D. I., & Iwara, A. I. (2014). Climate of Calabar and environs. Journal of Meteorology and Climate Science, 2(1), 12-18.

United Nations. (2022). World water development report: Groundwater. UNESCO.

Weather Atlas. (2024). Climate data for Calabar, Nigeria

Wokem, G. N., & Lawson-Jack, B. (2016). pH and microbial population in groundwater. Journal of Environmental Microbiology, 18(2), 98-105.

World Health Organization [WHO]. (2011). Guidelines for drinking-water quality (4th ed.). WHO.

World Health Organization [WHO]. (2024). Guidelines for drinking-water quality (5th ed.). WHO.

Wuave, T. (2023). Chemical composition of landfill leachate. Journal of Environmental Chemistry, 20(3), 145-156.

Wynn, B., O'Connor, J., & Smith, P. (2009). Acidic water and metal leaching. Environmental Geology, 57(4), 789-796.

Youcai, Z. (2018). Leachate treatment and disposal. Elsevier.