Quality Assessment of Groundwater in Parts of Niger Delta, Southern Nigeria using Metal Pollution Index and Factor Analysis

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ABSTRACT

The Niger Delta is the operational base of major oil producing and servicing companies in Nigeria. The various human activities domiciled in the area have negatively impacted on the groundwater quality in the region. A total of 75 groundwater samples were collected and 11 heavy metals were analysed and used to assess the potability of the groundwater for domestic use. Water quality index, factor analysis and metal pollution index were employed in the study to ascertain the extent and level of heavy metal enrichment in the groundwater systems in the area.

The pollution ranking of the analysed metals are in the order of: very highly polluted (nickel), highly polluted (cadmium and lead), moderately polluted (cobalt, chromium, copper, iron, mercury and zinc) and lightly polluted (arsenic and manganese). Factor analysis revealed three factors, which signify three possible sources of pollution, with contributors to each factor having the same source.

The study identified oil spill, gas flaring, industrial effluents, acid rain, agrochemicals and indiscriminate dumping of refuse as the factors responsible for the deterioration of groundwater in the area. The local geology of the area which is characterized by high porosity and permeability provide the conductive pathway for easy movement of metals under acidic condition into the shallow groundwater system. Due to the monumental and devastating effects of hydrocarbon pollution in the area, the need to eradicate gas flaring and minimize oil spills as well as clean-up of contaminated sites in the area is advocated.

(Keywords: evaluation, groundwater quality, metal pollution index, factor analysis, Niger Delta)

INTRODUCTION

The increase in groundwater demand for various human activities has placed great importance on water science and management practice world-wide [1]. Each source of contaminant has its own damaging effects to plants, animals and ultimately to human health, but those that add heavy metals to soils and waters are of serious concern due to their persistence in the environment and carcinogenicity to human beings.

Unlike the organic pollutants which are biodegradable [2], heavy metals are not biodegradable [3], thus making them a source of great concern. Through food chain, the heavy metals bioaccumulate in living organism and reach levels that cause toxicological effects [4]. Human health, agricultural development and the ecosystem are all at risk unless soil and water systems are effectively managed and protected from heavy metal contamination [5]. A close relationship exists between groundwater quality and land use as various land use activities can result in groundwater contamination [6].

Waters are precious natural resources on which rely the sustainability of agriculture, industrialization and the civilization of mankind. Unfortunately, they have been subjected to severe exploitation and contamination due to anthropogenic activities resulting from artisanal mining, industrial effluents, dumpsites, gas flaring, oil spillage and petroleum refining leading to the release of heavy metals into the environment [7-8]. Industrialization and urbanization in the Nigerian oil-rich Niger Delta necessitated the choice of the study area, considering the impact of various anthropogenic activities on the groundwater system. The aquifer system in the area is largely unconfined, highly porous and permeable, and thus the tendency of contaminants infiltrating through the soil into the shallow water table cannot be overemphasized.

Since the discovery of oil in Nigeria more than fifty years ago, there has been no concerted and effective effort on the part of the government, let alone the oil operators, to evaluate and control environmental and health problems associated with the industry, thereby putting the host communities on the receiving end. Niger Delta is an oil-rich region with high amount of gas reserves. It covers about 20,000 km^2 within wetlands of 70,000 km^2 formed primarily by sediment deposition [9]. It is home to over 20 million people and 40 different ethnic groups, and its floodplain makes up 7.5% of Nigeria's total landmass [10]. It is the largest wetland and maintains the third largest drainage basin in Africa [11].

The region sustains a wide variety of crops, economic trees and a variety of freshwater fish than any ecosystem in West Africa. However, the region has lost majority of its natural endowments due to uncontrolled gas flaring, oil spillage and poor sanitary situation in the area [12 -13]. The Niger Delta is among the world's largest petroleum provinces and its importance lies on its hydrocarbon resources. It has been rated as the sixth largest oil producer and twelfth giant hydrocarbon province. The oil sector provides 20% of Nigerian's GDP and 95% of her foreign exchange earnings as well as 75% of budgetary revenues [12].

In Nigeria, immense tracts of mangrove forests have been destroyed as a result of petroleum exploration and exploitation in the mangroves and these have not only caused degradation to the environment and destroyed the traditional livelihood of the region but have caused environmental pollution (Figure 1) that has affected weather conditions, soil fertility, groundwater, surface water, rain water, aquatic and wildlife [6]. If this trend continues unabated, it is most likely that the food web complexes in this wetland might be at a higher risk of induced heavy metal contamination. This unhealthy situation continues to attract the interest of environmentalists and calls for evaluation of the impact of oil and gas exploitation activities in the coastal areas of Nigeria and this was part of what the current research investigated. The shallow depth and high permeability of the coastal plain sand aquifer of the Niger Delta has made the soil and groundwater system highly vulnerable to contamination. The strategic position of the Niger Delta in the socio-economic activities of Nigeria makes it imperative to have a good knowledge of the soil and groundwater quality status in this economically important region.

MATERIALS AND METHODS

Study Area Description

The study area lies within the eastern Niger Delta region of Nigeria between latitude 4°40'N to 5º40'N and longitude 6º50'E to 7º50'E (Figure 2). It covers parts of Port-Harcourt, Aba and Owerri, and a total area of approximately 12,056 km^2. The area is low-lying with a good road network system. The topography is under the influence of tides which results in flooding especially during the rainy season [14]. The prevalent climatic condition in the area comprises the rainy (March to October) and dry (November to February).

Geology and Hydrogeology of the Area

The study area (Port-Harcourt, Aba, Owerri and environs) is underlain by Pliocene-Pleistocene Benin Formation (Figure 2) belonging to the Benin Formation. The type locality of the formation is in Port-Harcourt, Aba and Owerri where the formation overlies the older Ogwashi-Asaba Formation. The formation consists of sands, sandstone and gravel with clays intercalating as lenses. The sands and sandstones are fine to coarse-grained, partly unconsolidated with varying thickness [15]. The Benin Formation is composed mostly of high resistant freshwater-bearing continental sands and gravels with clay and shale intercalations. The formation shares a geological contact with the Ogwahi– Asaba Formation in the northern part and with Alluvium in the southern part and thickens southwards into the Atlantic Ocean (Figure 2).

Figure 1: Pervasive environmental pollution and ecosystems degradation at the Niger Delta region, Nigeria. (a) Water pollution due to leakage from oil well head, (b) Incidence of oil well blow out during production, (c) Devastation of the vegetation in the area due to oil and gas exploitation and refining, and (d) Land degradation caused by leakage from oil pipeline in the area.

Groundwater Sampling and Laboratory Analysis

A total of 75 water samples were collected between January 2017 and November 2019 using polyethylene bottles of one liter capacity for cations analysis. The water from boreholes were allowed to flow for about 2 minutes before it is sampled (collected), and containers were thoroughly washed and rinsed with the water to be collected into them.

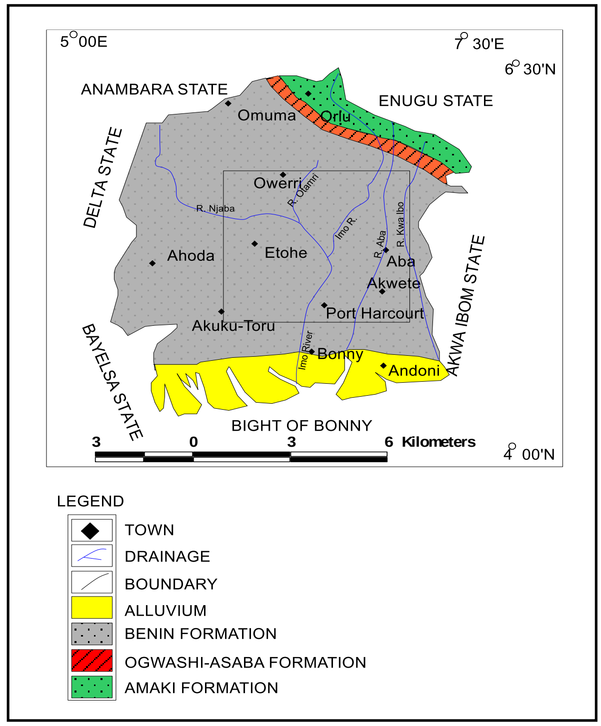

Figure 2: Geological Map of the Eastern Niger Delta showing the Study Area.

Samples for the determination of cations were stabilized with a drop of dilute hydrochloric acid on collection. Control samples were collected far away from the flow stations, gas flaring point and dumpsites and also sent to the laboratory for relevant analyses. All the samples were preserved by refrigeration and analyzed within 24 hours of collection. The pH was determined *in situ* using portable Martini MI 806 with sensitive probe. Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) Model-Optima 200 by Perkin Elmer was employed to the determine cations. The analyses were carried out in accordance with the American Public Health Association standards [16]. Some of the samples were sent to Activation Laboratory Ltd (ActLab), Ontario, Canada for analysis while others were analyzed at the National Agency for Food and Drug Administration and Control (NAFDAC) Regional Laboratory, Anambra and Department of Plant Science and Biotechnology Laboratory, University of Port-Harcourt, Nigeria.

RESULTS AND DISCUSSION

Heavy Metals

Heavy metals are metallic chemical elements that have a relatively high density. and are toxic or poisonous at low concentrations. They refer to chemical elements with a specific gravity that is at least 5 times the specific gravity of water. The specific gravity of water is 1 at 4°C (39°F). Specific gravity is a measure of density of a given amount of a solid substance when it is compared to an equal amount of water. The heavy metals cannot be degraded or destroyed and can enter our bodies through food, drinking water and air. The metals are dangerous because they bioaccumulate. Bioaccumulation is an increase in the concentration of a chemical in a biological organism over time when compared to the chemical's concentration in the environment. The 11 heavy metals investigated in the present study include lead, cadmium, copper, nickel, zinc, chromium, cobalt, mercury, arsenic, manganese and iron.

The concentrations of lead in the groundwater ranged between 0.02 mg/l to 1.05 mg/l with an average value of 0.04 mg/l. The values were far higher than the maximum permissible limit of 0.01 mg/l [17]. High concentration of lead in the groundwater may be attributed to the crude oil production in the region with an emphasis to the devastating effects of oil spills and gas flaring. It is carcinogenic and affects several organs of the human body, including the nervous system, the blood system, the kidney, the cardiovascular system and the reproductive system. The adverse effects of lead on the nervous system of children includes reducing intelligence and behavioral abnormalities. Studies have found a positive correlation between lead exposure and measured intelligence quotient (IQ) of school-age children [18].

Copper is one of several heavy metals that are essential to life despite being as inherently toxic due to accumulation effect. The concentration of copper ranged between 0.03 mg/l and 1.15 mg/l with a mean value of 0.08 mg/l (Table 1). Some locations have concentrations above the maximum recommended value of 1.00 mg/l [17]. The observed higher concentration value in some locations is as a result of leachates from untreated industrial wastes, dumpsites, damaged equipment and machinery used in oil production in the area. Gastrointestinal disorder in human can be due to elevated copper concentration in drinking water [17].

Nickel concentrations ranged from 0.01 mg/l to 0.07 mg/l with an average value of 0.32 mg/l (Table 1). The mean concentration of nickel is slightly higher than the maximum acceptable limit of 0.02 mg/l recommended by [17]. Nickel is a very abundant element in the environment and is found primarily combined with oxides or sulphides. Nickel particles in the air via tobacco smoke, auto exhaust and gas flaring settle to the ground or are taken out of the air as rain. Leachate from dumpsites and industrial effluents can also enrich nickel concentration in the groundwater. The most common adverse health effect of nickel in humans is an allergic reaction [4].

Table 1: Statistical Summary of the Groundwater Analysis in the Study Area.

Parameters	Minimum (mg/l)	Maximum (mg/l)	Mean (mg/l)	NSDWQ [17]
pH	4.85	7.74	5.62	6.500-8.500
Arsenic	0.001	0.016	0.007	0.01
Cadmium	0.07	0.19	0.10	0.003
Chromium	0.02	0.15	0.07	0.05
Cobalt	0.00	0.08	0.03	0.02
Copper	0.03	1.15	0.08	1.00
Iron	0.05	6.87	0.62	0.30
Lead	0.02	1.05	0.04	0.01
Manganese	0.01	0.78	0.19	0.20
Mercury	0.001	0.004	0.003	0.001
Nickel	0.01	0.40	0.18	0.02
Zinc	0.03	8.15	1.70	3.00

The concentration of zinc varied from 0.03 mg/l to 8.15 mg/l and a mean value of 1.70 mg/l (Table 1). This value falls below the permissible limit of 3.00 mg/l [17]. Zinc is one of the commonest elements in the earth's crust. It's found in air, soil, and water, and is present in all foods. It has many applications such as coating to prevent rust, in dry cell batteries and mixed with other metals to form alloys such as brass and bronze. Zinc compounds are widely used in industry to make paints, rubbers, dyes, wood preservatives, ointments, household utensils, castings and printing plates. Zinc is released into the environment through mining, steel production, crude oil production, gas flaring and dumpsites. Zinc is an essential element in our diet. Too little zinc can cause health problems, but too much zinc is also harmful [19-21].

The concentration of chromium ranged from 0.02 mg/l to 0.15 mg/l with a mean value of 0.07 mg/l. The mean concentration is higher than the maximum permissible limit of 0.05 mg/l recommended by the NSDWQ [17]. Chromium is a naturally occurring element found in rocks, soil, plants, animals, and in volcanic dust and gases. Chromium is used in manufacturing chrome-steel or chrome-nickel-steel alloys (stainless steel) and other alloys, bricks in furnaces, and dyes and pigments, for greatly increasing resistance and durability of metals and chrome plating, leather tanning, and wood preserving. It also helps insulin to maintain normal glucose levels [22]. Chromium is toxic at higher concentration and can damage the human organs such as the lungs, kidney, liver, stomach and intestines [23].

The concentrations of cobalt in the groundwater ranged from 0.00-0.08mg/l with an average value of 0.03 mg/l. Cobalt used in industry is imported or obtained by recycling scrap metal that contains cobalt. It is used to make alloys, paints, large appliances, and kitchen-wares. Cobalt has also been used as a treatment for anemia, as it aids red blood cell production [24]. The International Agency for Research on Cancer has revealed that cobalt is a possible carcinogen to humans. Studies in animals have shown that cobalt causes cancer when placed directly into the muscle or under the skin [22, 25].

The concentrations of mercury ranged from 0.001 to 0.004 mg/l and an average value of 0.003 mg/l. as against the maximum permissible limit of 0.001 mg/l [17]. Mercury also combines with carbon to form organic mercury compounds. The most common organic mercury compound is methyl mercury, which is produced mainly by small organisms in the water and soil. The more mercury becomes available in the environment the more methyl mercury is produced by these small organisms. Metallic mercury is used to produce chlorine gas and caustic soda, and also in thermometers, amalgams (dental fillings) and batteries [26]. Mercury is used in scientific and electrical equipment, in the electrolytic production of chlorine and sodium hydroxide; and as a catalyst in polyurethane foam production. It enters the water or soil from natural deposits, disposal of wastes, and the use of mercury-containing fungicides [27]. At high concentrations, it causes severe respiratory irritation, central nervous system, digestive disturbances, developing fetus, brain and kidney damage.

The concentration of arsenic ranged between 0.001 mg/l and 0.016 mg/l with a mean value of 0.007 mg/l. When arsenic enters the environment, it does not evaporate, instead it can be absorbed in the soil, dissolve in groundwater or release in the atmosphere via burning of arsenic compounds [28]. Arsenic is the most common cause of acute heavy metal poisoning in adults and is released into the environment by the smelting process of copper, zinc, and lead, as well as by the manufacturing of chemicals and glasses [29]. Arsenic gas is a common by-product produced by the manufacturing of pesticides that contain arsenic. It is also found in paints, rat poisoning, fungicides and wood preservatives. It causes damage to blood, kidney, skin, central nervous and digestive systems [30].

The concentration of manganese ranged from 0.01 mg/l to 0.78 mg/l with an average value of 0.29 mg/l, as against the acceptable value of 0.2 mg/l [17]. Decomposition and subsequent leaching industrial effluents are probable sources of groundwater enrichment with manganese. It is an essential element for plants and animals, and it is used in products such as batteries, glass and fireworks [31]. Potassium permanganate is used as an oxidant for cleaning, bleaching and disinfection purposes. Other manganese compounds are used in fertilizers, fungicides and as livestock feeding supplements [32].

The concentration of iron ranged from 0.05 mg/l to 6.87 mg/l with a mean value of 1.62 mg/l as against the maximum recommended value of 0.30 mg/l [17]. Iron is an essential nutrient that is vital to the processes by which cells generate energy. Iron can also be damaging when it accumulates in the body. The implication of the high iron content is that the water may have taste, color and other aesthetic problems such as hemochromatosis. Because iron can exist in different ionic states, iron can serve as a cofactor to enzymes involved in oxidation-reduction reactions. In every cell, iron works with several of the electron-transport chain proteins that perform the final steps of the energy yielding pathways. Pregnancy places iron demands on women as it is needed to support the growth of the fetus and blood loss during childbirth. Organs affected by iron are the pancreas, liver, kidneys, brain, heart and joints [1].

Metal Pollution Index

Metal pollution index (MPI), Eqn. 1, is a method of rating that shows the composite influence of individual metals on the overall quality of water. The rating is a value between zero and one, reflecting the relative importance individual quality considerations. The MPI represents the sum of the ratio between the analyzed parameters and their corresponding national water standard value (Table 2).

The higher the concentration of a metal compared to its maximum allowable concentration, the poorer the quality of the water [33]. It also gives an overview of the quality status of the groundwater in any area with reference heavy metal contamination. It has wide applications and it is used as an indicator of the potability of groundwater systems in any given geological environment [27]. The computed metal pollution index for the groundwater systems in the area ranked the degree of metallic pollution from very highly polluted to lightly polluted (Table 2). This implies that all the analyzed 11 metals have in various degrees degraded the potability of the groundwater in the area. The possible sources of the pollution are oil spills, gas flaring, dumpsites, industrial effluent and acid rain.

$$MPI = \sum_{i=1}^{n} \frac{C_i}{MAC_i} \quad \textbf{(1)}$$

Where C_i is the mean concentration and *MAC*: maximum allowable concentration.

Water quality and its suitability for drinking purpose can be examined by determining the metal pollution index.

Water Quality Index

Water quality index (WQI) of the groundwater was determined in order to ascertain the overall quality status of groundwater in the area. The WQI was computed from the point view of suitability of the water for domestic use and it was achieved by using the weighted arithmetic index method.

The quality rating scale for each parameter q_i was calculated by using the equation:

$$q_i = (C_i/S_i) \times 100 \quad \textbf{(2)}$$

Table 2: Computed Metal Pollution Index for the Groundwater System in the Area.

Parameters (mg/l)	C_i	MAC_i	MPI Value	Rating
Arsenic	0.007	0.01	0.70	Lightly polluted
Cadmium	0.11	0.02	5.50	Highly polluted
Cobalt	0.02	0.01	2.00	Moderately polluted
Chromium	0.07	0.05	1.40	Moderately polluted
Copper	0.8	1.00	1.90	Moderately polluted
Iron	0.62	0.30	2.10	Moderately polluted
Lead	0.08	0.01	8.00	Highly polluted
Manganese	0.19	0.20	0.95	Lightly polluted
Mercury	0.003	0.001	3.00	Moderately polluted
Nickel	0.28	0.02	14.00	Very highly polluted
Zinc	0.17	3.00	1.57	Moderately polluted

< 0.01 = Very lightly polluted; 0.01-1.0 = Lightly polluted; 1.0-5.0 = Moderately polluted; 5.0-10.0 = Highly polluted; > 10.0 = Very highly polluted

A quality rating scale (q_i) for each parameter is assigned by dividing its mean concentration (C_i) in each water sample by its respective Nigerian Standard for Drinking Water Quality (S_i) [17], and the result multiplied by 100.

The Relative weight (w_i) was obtained by a value inversely proportional to the recommended standard (S_i) of the corresponding parameter:

$$w_i = 1/S_i \quad \textbf{(3)}$$

The overall WQI was calculated by aggregating the quality rating (q_i) with unit weight (w_i) linearly in accordance with Amadi *et al*. [34].

$$MPI = \sum_{n=1}^{i=n} q_i w_i \quad \textbf{(4)}$$

Where:

q_i: the quality of the i^{th} parameter,
w_i: the unit weight of the i^{th} parameter and
n: the number of the parameter considered.

The element-by-element WQI index was computed (Table 3), and the overall water quality of the area was therefore obtained using the formula:

$$WQI = \frac{\sum q_i w_i}{\sum w_i} \qquad \textbf{(5)}$$

WQI = 623346.374/ 1663.123 = 374.82

The computed overall WQI mean value is 374.82, and it implies that the groundwater in the area is unsuitable for drinking. The high value of WQI obtained can be attributed to the level of groundwater deterioration via heavy metal enrichment. The problem of acid rain ravaging the entire region as a result of uncontrolled gas flaring over the years is capable rendering the groundwater unfit for human consumption besides undue environmental pollution from oil spills, indiscriminate dumping of both solid and liquid wastes. The quality of the groundwater in the area varies based on the proximity to identified pollution sources (oil spill sites, gas flaring sites, crude oil terminals, dumpsites and effluent discharge points). The results of the laboratory analysis revealed that the further away the samples are from these sites, the lower the concentration of the metals and vice versa. The groundwater quality in the area varied in the following descending order: excellent (04%), good (13%), poor (21%), very poor (29%) and unsuitable (33%) as shown in Table 4.

Factor Analysis (FA)

The factor analysis is a useful tool in the study of the relationship among variables and for categorizing the variables into groups based on source, origin or type that are mutually correlated within a data set [25]. Principal component analysis data, when varimax rotated, gives rise to factor analysis and such rotations are very useful in the standardization of data sets. Clusters with eigenvalues higher than one are used to generate the varifactors, accounting for 73.50 percent of the total variance.

Factor-1 accounts for 36.40% of the total variance (Table 5) with pH, copper, zinc, iron and manganese as the contributing factor. They are used in electroplating, alloys, roofs, cooking utensils, coins and paint manufacture. Their enrichment in the groundwater may be attributed to the weathering, decomposition and leaching of materials that contain these metals. It could also arise from the impacts of oil spills, gas flaring and decomposition of drilling wastes. Iron could also be as a result of leaching/infiltration from the lateritic overburden into the shallow groundwater table in the area. The mobility of metals in water is a function of pH, since acidic condition enhances the propensity of metals to be mobilized in solution [32].

Factor-2 has a moderate loading of 27.60% of the total variance (Table 5) and is attributed to cadmium, chromium, cobalt and nickel. These metals are raw materials used in making alloys, batteries, electronics, plastics, glass and electrical wiring. When these products are damaged, they are discarded and during decomposition processes, these metals are leached away, and they find their way into the porous and permeable shallow aquifer system in the area. They may also be attributed to oil spills and gas flaring activities taking place in the area as well as indiscriminately dumped drilling wastes in the area.

Factor-3 has the lowest loading of 10.50% with arsenic, lead and mercury (Table 5). These metals are carcinogenic at low concentration and their presence in the groundwater system is due to the discharge of untreated industrial effluent from the industries domiciled in the area as well as gas flaring and oil spill activities ravaging the region.

The efficacy of factor analysis in interpreting the groundwater geochemical data as well as identifying and categorizing pollutants sources and types has been successfully demonstrated in this study.

CONCLUSIONS

This study has clearly established that gas flaring, oil spills, agrochemicals, industrial effluents and indiscriminate dumping of wastes constitute a major source of water pollution in the oil producing region of the eastern Niger Delta, Nigeria. It is remarkable to note that concentrations of these heavy metals consistently decreased away from the gas-flaring points, spill-point, effluent-point, flow-stations and dumpsites.

Table 3: Computed WQI Values for the Study Area.

Parameters (mg/l)	C_i	S_i	q_i	w_i	q_iw_i
pH	5.460	7.500	82.267	0.133	10.942
Arsenic	0.007	0.010	70.000	100.000	7000.000
Cadmium	0.14	0.003	4666.667	333.333	155555.667
Chromium	0.070	0.050	140.000	20.000	2800.000
Cobalt	0.030	0.020	150.000	50.000	7500.00
Copper	0.080	1.000	8.000	1.000	8.000
Iron	0.620	0.300	18.600	3.333	61.994
Lead	0.080	0.010	800.000	100.000	80000.000
Manganese	0.190	0.200	95.000	5.000	475.000
Mercury	0.003	0.001	300.000	1000.000	300000.000
Nickel	0.280	0.020	1400.000	50.000	70000.000
Zinc	0.700	3.000	23.333	0.333	7.769

Table 4: Water Quality Classification Based on WQI Value.

WQI value	*Water Status*	*Water samples (%)*
<50	Excellent	04
50-100	Good	13
100-200	Poor	21
200-300	Very Poor	29
>300	Unsuitable	33

Table 5: Factor Analysis of Groundwater from Eastern Niger Delta.

Parameters	**Factor 1**	**Factor 2**	**Factor 3**
Arsenic	0.080	0.258	**0.581**
Cadmium	0.298	**0.623**	0.329
Cobalt	0.074	**0.548**	0.211
Chromium	0.102	**0.644**	0.090
Copper	**0.765**	0.393	0.301
Iron	**0.648**	0.276	0.234
Lead	0.124	0.178	**0.598**
Mercury	0.005	0.080	**0.506**
Manganese	**0.688**	0.027	0.294
Nickel	0.129	**0.623**	0.023
pH	**0.847**	0.216	0.143
Zinc	**0.634**	0.129	0.079
Eigenvalue	3.421	2.536	1.476
% of Variance	36.40	27.60	10.50
Cumulative %	36.40	64.00	74.50

This has also been confirmed from the independent studies on the concentrations of heavy metals in groundwater system in most locations investigated in the current study. The study has revealed that the various anthropogenic activities domiciled in the area have led degradation of the environment and deterioration of the shallow groundwater system the region.

It is recommended that an end be put to gas flaring and oil spills in the area in order to save the groundwater system in this region from further contamination by toxic heavy metals.

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SUGGESTED CITATION

Amadi, A.N. B.O. Udoh, T.M. Ozoji, W.G. Akande, I. Shaibu, M.A. Dan-Hassan, S.U. Hussaini, and A.S. Oguntade. 2020. "Quality Assessment of Groundwater in Parts of Niger Delta, Southern Nigeria using Metal Pollution Index and Factor Analysis". *Pacific Journal of Science and Technology*. 21(1):280-289.

Pacific Journal of Science and Technology