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Water quality evaluation using water quality index and pollution model in selected communities in Gbaramatu Kingdom, Niger Delta, Nigeria

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Drinking water quality is a critical factor affecting human health particularly in natural resource-dependent countries including Nigeria. Hydrocarbon related pollution, mining waste, microbial load, industrial discharge and other anthropogenic stressors degrade drinking water quality in coastal communities and pose serious public health and ecological risks. This study evaluated the physicochemical properties of drinking water in selected communities (Okerenkoko, Kurutie, and Oporoza) located in Gbaramatu Kingdom, in the Niger Delta region of Nigeria, in order to assess the water quality using the Water Quality Index (WQI) and pollution models. Nitrate, Chromium, Cadmium, Copper, Lead, Aluminium, pH, Total Hardness, Total Dissolved Solids, Cyanide, and Residual Chlorine were measured in twelve selected locations across the three communities. The WQI results of the analyzed water samples in the area indicated that they exceeded the critical WQI value of 100, with a mean pH of 8.11 ± 0.32, indicating unsuitability for consumption. Nickel ranging from 0.014 to 0.176 mg/L and residual chlorine 11.6 to 7407 mg/L were the major contributors to the degradation of water quality and exceeded the WHO recommended limit of 0.02 and 0.25 respectively. While groundwater had better organoleptic properties compared to surface and rain water, the geo-accumulation index showed that water sources in the area vary from moderately to heavily contaminated with Ni and Cd. These WQI and pollution model results necessitate an urgent response from local stakeholders to address the water quality deterioration, such as providing alternative water supplies, to minimize the potential health risks to the local population.

Key words: Water quality index, contamination index, oil pollution, chemical parameters, geo-accumulation index.

INTRODUCTION

Access to safe and potable drinking water is a basic need of mankind and a human right, including health and food. This justifies the United Nations Sustainable Development Goal 6, which seeks to achieve access to clean water

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and sanitation for all by 2030. The goal seeks to improve water quality by limiting contamination, eliminating dumping and reducing release of chemical substances and materials into the water, to increase safe use and reuse of water globally (WHO, 2019; UNEP, 2021).

Water is needed and used globally by humans irrespective of nationality, tribe, region, religion, color or societal status because it is one of the greatest factors that determine human health and development (Li and Wu, 2019; Delpla et al., 2020). Despite its importance, the quality of available drinking water is often compromised due to pressures exerted on it by growing population, agricultural production, natural resource exploration and mining, urbanization, and industrialization (Naeem et al., 2013; Li and Wu, 2019). With increasing climate change challenges, rivers drying up, and wetlands being reclaimed, the continuous pollution of water resources by anthropogenic activities has cumulative impacts on humans. Anthropogenic activities including dumping of mixed waste in water bodies, onshore and offshore hydrocarbon spillages, and open defecation contribute potentially toxic elements (PTEs) to water resources (Naeem et al., 2013). Hydrocarbon contamination for example, exposes surface and underground water to toxic elements including benzene (which is a carcinogenic substance), and affects the quality of drinking water (UNEP, 2011). Considering that water quality is a health determinant, consumption of water contaminated either by biological or chemical means may likely pose serious health risks to public health. An estimated 2.3 billion people suffer from water-borne diseases globally (Ahmed et al., 2020), while 485,000 people die from diarrhoea as a result of contaminated drinking water yearly (WHO, 2019). The World Health Organization (WHO) reports that water contamination contributes to 70% of different diseases and 20% of cancers on a global scale (WHO, 2022).

Discharge of domestic and industrial effluent wastes, leakage from water tanks, marine dumping, and radioactive waste into water bodies constitute contamination, and degrades water quality. When this happens, these water bodies accumulate heavy metals and pose harm to humans, animals and entire ecosystem. The toxicity of PTEs or specifically, heavy metals (for example, cadmium, zinc, lead, copper, manganese, magnesium, iron, arsenic, silver, and chromium) from mining, smelting or hydrocarbon exploration activities can have lethal and harmful effects on human health and the ecosystem (Vanloon and Duffy, 2005). In addition, toxins in industrial waste have been identified as a major cause of immune suppression, cancer, reproductive failure and acute poisoning. Infectious diseases, like cholera, typhoid fever, dysentery, polio, trachoma, and abdominal pain (Juneja and Chauhdary, 2013) and other gastroenteritis, including diarrhea, vomiting, skin and kidney problem are spreading through contaminated water (Khan and Ghouri, 2011; Chima and Digha, 2009; Digha and Abua, 2016).

Considering the importance of water quality, many nations have developed systems and agencies to establish water quality monitoring programs. These systems help decision-makers to understand, interpret and use available data to enhance the protection of water resources (Behmel et al., 2016). As a result of effective monitoring and access to water quality data to protect resources and human health, many countries have reformed their water regulatory framework towards sustainable development as recommended by Agenda 21 (UNEP, 1992). In Nigeria for example, government have developed a number of initiatives to protect water resources. In November 2018, the Nigeria government declared a state of emergency in the water, sanitation and hygiene (WASH) sector, as part of measures to protect increasingly degraded water resources and the upsurge of water borne diseases (Wada et al., 2021). However, this initiative is yet to yield desired outcomes due to limited finance, poor service delivery, lack of stakeholder collaboration and adhoc implementation (Musa et al., 2021). Nigeria intends to achieve 100% access to clean water and sanitation by 2030, with focus on rural communities. Although these efforts have focused on biological contaminants, achieving this will require significant investments in building necessary infrastructure, maintaining existing ones and awareness creation. Also, it will require a stringent monitoring of PTEs as they constitute a major contributor to water contamination. In terms of investment, Nigeria needs an estimated $2.7 billion USD to achieve outlined targets by 2030 (Musa et al., 2021), and the government is expected to provide 25% of the funds, while 75% will be incurred by households to build toilets. Households in the face of the current economic woes are focused on basic needs (that is, shelter and food) and would likely continue open defecation in the nearest future.

THE NIGER DELTA AND WATER QUALITY

Since the late 1950s when Nigeria discovered commercial quantity of oil and commenced exportation, the Niger Delta region has experienced several oil spill incidences. For example, the 2008/09 Bodo oil spill affected surface and underground water sources, farmlands and impacted over 69,000 households (Pegg and Zabbey, 2013). In the last six decades of oil exploitation, the region has experienced several oil spills that have resulted in the contamination of over 4,000 sites, mostly affecting local communities. Specifically, within the Niger Delta region, Gbaramatu Kingdom host the Nigeria Maritime University, and constitute a hotspot for oil and gas exploratory activities, with attendant soot, hydrocarbon contamination, and locals in unplanned settlements along the Escravos coastline (Figure 1). Gbaramatu Kingdom

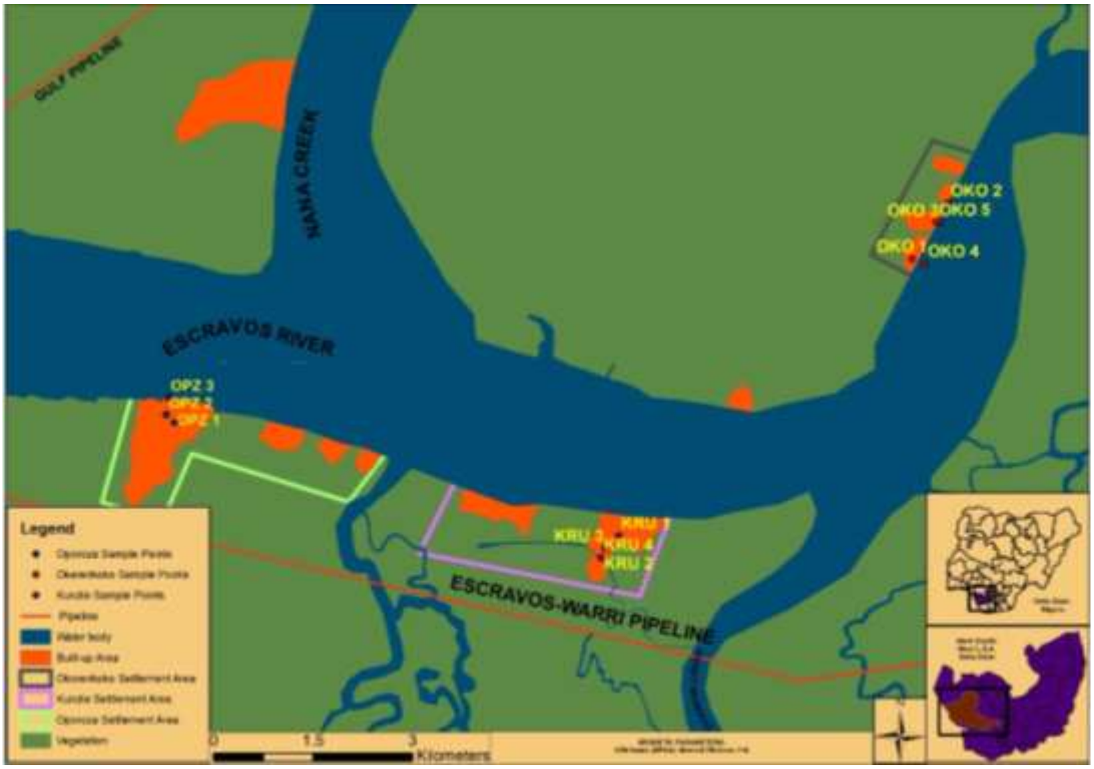

Figure 1. Gbaramatu Kingdom showing the sampling points.
Source: Authors.

hosts many oil and gas infrastructures including oil and gas pipelines, gas flaring chimneys, oil wells, oil fields, oil drilling platforms, and sub-stations. The area is well known for mangrove degradation, and contaminated surface and underground water following oil activities in the area. Thus, constituents of hydrocarbon are the major sources of PTEs in water while biological contamination are caused by WASH related activities such as open defecation. Decline in water quality are primarily caused by PTEs and biological contamination in coastal communities. Most water contamination incidences reported in the Niger Delta region of Nigeria has been attributed to PTEs. This is because the region, which comprises nine states, situated at the apex of the Gulf of Guinea on the west coast of Africa, is the hub of oil and gas production in Nigeria (Sam et al., 2022). It is one of the most bio-diverse regions, with the largest wetland in Africa and second largest delta globally (Izah, 2018; Anwan et al., 2016), with ecologically sensitive areas including coastal barrier islands, mangrove swamps, lowland forest and fresh water swamps (Sam et al., 2017).

Within the Niger Delta region, and specifically, the coastal communities in Gbaramatu Kingdom, the provision of drinking water, and the determination of the quality of water consumed is an individual responsibility (de Zeeuw et al., 2018). Individual households derive their drinking water from different sources depending primarily on economic status and social stratification, with no water quality monitoring or treatment measures. While most locals depend on surface waters and shallow boreholes as primary source of drinking water, the wealthy and influential people in the semi-urban areas derive drinking water from underground sources and provide a level of treatment before consumption. Due to the toxic and bio-accumulative nature of PTEs such as hydrocarbons and its constituents including benzene and phenols, communities that depend on surface and underground water sources for drinking water are exposed to potential ecological and public health risks. Understanding the status of drinking water quality using an empirical approach would provide scientific evidence for decision-making for protecting and managing water quality, and take immediate action where necessary. This would require the use of effective water quality assessment and pollution models to achieve reliable results, and enhance confidence in management decisions. Different water quality assessment strategies have been developed and applied (Tian and Wu, 2019; Su et al., 2019; Li and Wu, 2019). For example, Fathi et al. (2018) used a multivariate method and WQI to assess water quality in Baheshtabad River in Iran. Fatoba et al.

(2016) used a potential ecological risk assessment to evaluate water quality and ecological risk in Kokori and Kolo Creek while NPI analysis identified Cd, Ni, and Cr as the primary pollutant contributors. Owamah et al. (2020) also used WQI to evaluate the state of groundwater in the Emevor community in the Niger-Delta region of Nigeria. Despite the importance of water quality as a health determinant and parameter for measuring quality of life, most studies in the Niger Delta have focused on the impacts of hydrocarbon on water resources resulting in a dearth of data on the relative heavy metals toxicity and potential human health risk. Also, there is an unassuming lack of evidence in literature on the biology, ecology, physiology and hydrology of the Gbaramatu Kingdom, despite its strategic economic importance to the nation. This empirical study provides baseline datasets on water quality in the Gbaramatu Kingdom, and highlighted the potential health risk posed to human health and the environment.

MATERIALS AND METHODS

Study area

Gbaramatu Kingdom in Nigeria's Niger Delta region is home to coastal communities such as Oporoza, Okerenkoko, Kurutie, Isaba, and Diebiri. It covers an area of 1,722 km^2 (665 sq mi) with an estimated population of 963,353. The majority of the population consists of farmers and fishermen living in scattered settlements along the Escravos coastline. The kingdom is also notable for hosting two campuses of the Nigeria Maritime University in Okerenkoko. The selected communities for this study are Okerenkoko, Kurutie, and Oporoza, located along the Escravos river coastline. These areas are economically important due to oil and gas infrastructure and exploratory activities, including shipping and oil platform movement. The communities were chosen based on their dense population, consumption of contaminated water, and high level of involvement in artisanal crude oil refining as a livelihood option (Sam et al., 2022; Sam and Zabbey, 2018; Naanen, 2019). Despite hosting significant oil infrastructure, the standard of living in these communities is remarkably low. Open and indiscriminate dumping of mixed waste along roadsides and riverbanks is common, leading to water contamination. Additionally, the use of agrochemicals without proper government control and weak waste management measures contribute to the contamination of water bodies. The area also suffers from visible atmospheric soot, oil spills on water and farmland, and gas flaring, all of which pose additional stressors on existing drinking water sources in the region. Gbaramatu Kingdom is located in Warri Southwest Local Government Area, Delta State, in the Niger Delta region of Nigeria. It comprises of several coastal communities including Oporoza, Okerenkoko, Kurutie, Isaba, Diebiri. With an estimated population of 963,353, covering a landmass of 1,722 km^2 (665 sq mi), the local population are predominantly farmers and fisherfolks, living in scattered settlements littered along the Escravos coastline (Figure 1). The Kingdom hosts two campuses of the Nigeria Maritime University, Okerenkoko. The communities in Gbaramatu Kingdom are situated in undulating mangroves and endowed with natural water sources like rivers and creeks. The study was conducted in three selected communities in the Kingdom including Okerenkoko, Kurutie and Oporoza (Figure 1), located along the coastline of the Escravos river, which is of significant economic value to the nation and state government, considering the oil and gas infrastructure and exploratory activities (for example, shipping and moving oil platforms), undertaken in the area. These communities were selected because they are densely populated, consume smelly water and the area is highly oil-industrialized. Most importantly, due to lack of meaningful employment, a critical mass of youths is involved in artisanal crude oil refining activities (boiling stolen crude oil to derive petrol, diesel and kerosene), as a means of livelihood (Sam et al., 2022; Sam and Zabbey, 2018; Naanen, 2019). While this is a general practice in the Niger Delta region, its prevalence in coastal communities where access to crude oil pipelines is unhindered, is high (Naanen, 2019). Also, despite hosting significant oil infrastructure (for example, pipelines, well heads, flow stations and floating crude oil platforms) and their contributions to national economy, the standard of living is extremely low. For example, they practice open and indiscriminate dumping of mixed wastes along road sides and river banks. These wastes end up in water bodies during rainfall thereby contributing to the contamination level in water bodies. Considering limited government control on the use of agrochemicals and the weak waste management measures, the local population apply unquantifiable amount of nitrogen, phosphorus, potassium, urea and manganese fertilizers to support agricultural yield. The cumulative effect of conventional and illegal oil exploration activities in the area has resulted in visible soot (particulate matter) in the atmosphere, oil spills on surface water and farmlands, and gas flaring, thus increasing anthropogenic stressors pressuring existing drinking water sources in the area.

Sample collection and analyses

Groundwater samples were collected from major points in each of the selected communities alongside their surface water. A total of twelve points were sampled (Table 1), and the water samples were collected in duplicates. The water samples were collected during the peak of the rainy season in June 2022. A total of 24 water samples were collected in airtight plastic containers sterilized with ethylene oxide gas, stored in a refrigerator, and transported in ice to environmental laboratory for analysis. The organoleptic properties (color, taste and odor) of the water samples were determined by sensory analysis, while the physicochemical analysis of the water samples was done using the standard method of APHA (2017). The parameters measured include pH–pH meter, conductivity-conductivity meter, Dissolved Oxygen -Winkler's method, alkalinity–acidimetric titration method, nitrate–sodium salicylate method, residual chlorine–titration using potassium iodide, cyanide–direct spectrophotometric method using a picric acid reagent, total dissolved solids (TDS)–evaporation method (APHA method 2540 C), and total hardness (TH)–EDTA titrimetric method. The heavy metals, Cd, Pb, Ni, Cu, Zn, Fe, Al, and Cr, were determined by flame atomic absorption spectrometry (APHA, 2017).

Statistical analysis

The statistical analysis was conducted using the ORIGIN 2021 statistical application. Descriptive statistics were used to calculate the mean, standard deviation, and range of the physicochemical properties. Principal component analysis (PCA) determined the existence of multi-collinearity between the variables measured. Water contamination was assessed using the Water Quality Index (WQI), the Geo Accumulation Index (Igeo), and Nemerow Pollution

Table 1. Sample stations and coordinates.

S/N	Sample Stations	Sample code	Latitude	Longitude
1.	Okerenkoko Staff Quarters	OKO-1	5.621193	5.388012
2.	George's Quarter	OKO-2	5.629490	5.393379
3.	Well water	OKO-3	5.626549	5.392250
4.	Okerenkoko River	OKO-4	5.620496	5.389960
5.	Rain water	OKO-5	5.626644	5.391647
6.	Kurutie community water	KRU-1	5.580183	5.344223
7.	Kurutie Students' hostel	KRU-2	5.576934	5.341597
8.	Kurutie Staff Quarters	KRU-3	5.578266	5.578266
9.	Kurutie River	KRU-4	5.576934	5.341597
10.	Locally produced sachet water	OPZ-1	5.597251	5.278256
11.	Oporoza treated water	OPZ-2	5.59845	5.27706
12.	Oporoza River	OPZ-3	5.601064	5.277341

Source: Authors

Index (PN).

Water Quality Index (WQI)

The water quality index (WQI) is a measure that is used to evaluate the status of water over a period of time. WQI transforms data on water quality into information that can be understood by the general public. Odia and Nwaogazie (2017) and Nwaogazie et al. (2018) have utilized WQI to evaluate water quality. The equation is given as:

$$\text{WQI} = \frac{\sum QjWj}{\sum wj} \quad (1)$$

The quality score scale (Qj) for each parameter is calculated via Equation (2):

$$\text{Qj} = \frac{Vj - Vo}{Sj - Vo} \text{ X } 100 \quad (2)$$

where: v_j is the expected concentration of the nth parameter in water samples analysed; v_0 is the optimal value of evaluated water parameter in a sample of normal water which is usually zero except pH = 7.0 and dissolved oxygen, DO = 14 mg/l, s_j is the standard value specified for the nth parameter which for this study was World Health Organization (WHO, 2011; 2017) for drinking water quality.

The unit weight (wj) for each water quality parameter is evaluated using:

$$\text{Wj} = \frac{K}{Sj} \quad (3)$$

where k = proportionality constant and is evaluated by:

$$\text{K} = \frac{1}{\sum \frac{1}{Sj}} \quad (4)$$

The classification of the index ranges from 0 to 100 (Excellent to unsuitable water quality) depending on the values scored.

Geo-accumulation index (Igeo)

The Igeo measures the degree of toxicity of heavy metals of interest (Muller, 1969). There are seven grades of the index, ranging from 0 to 6, with each grade having its own unique number of points (Uncontaminated to extremely contaminated). It is calculated as:

$$\text{Igeo} = log_2 \frac{C_n}{1.5xB_n} \quad (5)$$

Where, C_n is the mean concentration of the ith heavy metal in the water samples analyzed. B_n is the reference value.

Nemerow pollution index (NPI)

The Nemerow Pollution Index, also known as Row's Pollution Index, determines the total pollutant level and considers the properties of the analyzed water samples (Hakanson, 1980; Liu et al., 2017). It is calculated using the formula below:

$$\text{NPI} = \frac{C_n}{Sn} \quad (6)$$

where C_n = concentration of the nth parameter, S_n = prescribed maximum values of the nth parameter. Here, NPI ≤ 1 variables are responsible for only a minimal amount of water pollution while NPI>1 parameter associated to water contamination are found to be present in excess amounts.

RESULTS AND DISCUSSION

Organoleptic and chemical properties of water samples

The results of the organoleptic properties showed that all the water samples from the groundwater were unobjectionable in taste, odour and colour except for OKO-5 which was rainwater. In contrast, samples from

Table 2. Organoleptic properties of drinking water samples.

Communities	Sample ID	Appearance	Taste	Odour
Okerenkoko (OKO)				
Staff Quarters	OKO-1	Clear	Unobjectionable	Unobjectionable
George's Quarter	OKO-2	Clear	Unobjectionable	Unobjectionable
Well water	OKO-3	Clear	Unobjectionable	Unobjectionable
River	OKO-4	Brown	Objectionable	Objectionable
Rain water	OKO-5	Light Brown	Objectionable	Objectionable
Kurutie (KRU)				
General community water	KRU-1	Clear	Unobjectionable	Unobjectionable
Students' hostel	KRU-2	Clear	Unobjectionable	Unobjectionable
Staff Quarters	KRU-3	Clear	Unobjectionable	Unobjectionable
River	KRU-4	Darkish green	Objectionable	Objectionable
Oporoza (OPZ)				
Locally produced sachet water	OPZ-1	Clear	Unobjectionable	Unobjectionable
General community treated water	OPZ-2	Clear	Unobjectionable	Unobjectionable
River	OPZ-3	Objectionable	Objectionable	Objectionable

Source: Authors

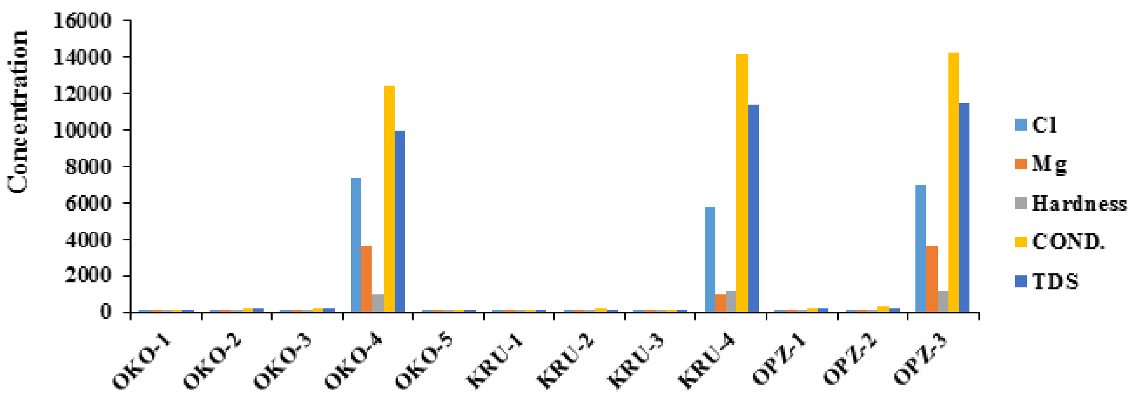

Figure 2. Spatial changes in some selected physicochemical parameters in the water samples.
Source: Authors.

the river had poor aesthetic standards (Table 2). The results of the concentrations of various physicochemical parameters characterized for the water quality assessment are summarized in Table 3. The mean, standard deviation, and standard values for each characterized parameter of the stations were also outlined. Each of the samples exhibited pH and alkalinity levels that were lower than the threshold values established by the World Health Organization (WHO, 2011; 2017). The water samples indicated a pH of 8.11 ± 0.32, and thus the water indicates alkaline. The pH level could be caused by minute quantities of dissolved minerals which allows the solubility and bioavailability of other compounds, particularly heavy metals, which are harmful to humans. OKO-4 indicated excessive acidic concentrations (41.4 mg/l) which is greater than the WHO-permissible limit of 8.5 mg/L. Research has shown that acidic water has a greater propensity to retain additional contaminants that are hazardous to human health (Afonne et al., 2020; de Meyer et al., 2017). Edet and Offion (2002) reported that leaching of altered rocks into groundwater by acidic rains could cause ground water acidity. The acidic nature of OKO-4 station could be attributed to organic particles deposited in the atmosphere of the community (for example, soot), which could have contributed to the acidic makeup of the water. Except for the samples taken from the brackish ecosystem (OKO-4, KRU-4, and OPZ-3) (Figure 2) the

Table 3. The mean result of the physicochemical parameters studied in the different water samples.

Parameter	OKO-1	OKO-2	OKO-3	OKO-4	OKO-5	KRU-1	KRU-2	KRU-3	KRU-4	OPZ-1	OPZ-2	OPZ-3	Max	Min	Mean	SD	WHO (2011;2017)
pH	8.17	8.09	8.13	8.25	8.2	8.19	8.18	8.19	7.13	8.45	8.22	8.1	8.45	7.13	8.11	0.32	6.5-8.5
SAL	0.06	0.17	0.1	5.25	0.01	0.11	0.12	0.11	4.67	0.23	0.18	6.94	6.94	0.01	1.5	2.54	0
Alkalinity (mg/L)	6.75	5.4	9.45	243	2.7	13.5	10.8	16.2	203	6.75	18.9	216	243	2.7	62.7	95.76	600
Acidity (mg/L)	4	5.05	4.51	41.4	2.08	6.5	2.54	5	4.06	2.5	5.52	7.6	41.4	2.08	7.56	10.78	8.5
R-Cl (mg/L)	37	69.4	23.1	7407	11.6	57.9	50.9	48.6	5787	34.7	116	6944	7407	11.6	1715.6	3034.39	0.25
Mg (mg/L)	5.88	9.81	58.8	3627	17.7	39.2	19.6	39.2	980	19.6	15.7	3598	3627	5.88	702.54	1386.51	70
Hardness (mg/L)	6.82	19.8	19.6	992	3.68	12.3	12.8	11.9	1134	18.5	20.2	1143	1143	3.68	282.88	487.87	425
COND. (µS/cm)	85.25	247.5	245	12400	46	153.75	160	148.75	14175	231.25	252.5	14287.5	14287.5	46	3536	6098.43	2500
TDS (mg/L)	68.2	198	196	9920	36.8	123	128	119	11340	185	202	11430	11430	36.8	2828.8	4878.75	1000
TURB (NTU)	0	0	2.19	2.34	1.8	1.44	0.62	0	0	0	0	3.95	3.95	0	0.83	1.27	5
DO (mg/L)	5.11	5.54	1.92	1.03	5.13	5.62	4.57	4.53	3.24	4.81	5.72	2.44	5.72	1.03	4.14	1.59	6
BOD (mg/L)	0.87	0.41	7.97	8.45	1.98	0.43	0.43	1.1	2.89	0.85	1.85	12.8	12.8	0.41	3.34	4.09	3
NIT (mg/L)	1.81	1.93	2.16	2.34	1.74	1.91	1.65	2.01	2.09	1.28	1.81	1.96	2.34	1.28	1.89	0.27	50
SUL (mg/L)	0.33	7.66	121	181	6.57	1.97	1.64	2.47	167	5.25	8.22	121	181	0.33	52.01	72.41	250
PHOS (mg/L)	0.49	0.41	0.59	0.55	0.61	0.61	0.55	0.56	0.63	0.58	0.53	0.48	0.63	0.41	0.55	0.06	2
TOC (%)	0.12	0.82	2.11	2.53	0.24	0.22	0.28	0.55	0.96	0.13	0.42	9.98	9.98	0.12	1.53	2.77	2
TOM (%)	0.26	1.76	4.54	5.44	0.52	0.47	0.60	1.18	2.06	0.28	0.90	21.46	21.457	0.258	3.29	5.96	200
Cy (mg/L)	0	0	0.012	0.018	0.004	0	0.004	0.003	0	0	0	0.01	0.018	0	0	0.01	0.05
Al (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.008	0	0.369	0.369	0	0.03	0.11	0.2
Pb(mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0	-	-	-
Cu(mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0	-	-	-
Ni (mg/L)	0.056	0.067	ND	0.134	0.014	0.038	0.033	0.028	0.171	0.024	0.037	0.158	0.171	0.014	0.06	0.06	0.02
Zn (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0			
Cd (mg/L)	ND	0.135	ND	0.169	0.157	ND	ND	ND	0.239	ND	0.005	0.369	0.369	0.005	0.09	0.12	0.005
Cr (mg/L)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0	-	-	-
Fe (mg/L)	0.006	ND	1.605	0.561	ND	ND	ND	ND	0.376	ND	0.436	0.458	1.605	0.006	0.29	0.47	0.3

Source: Authors

levels of total hardness (TH), magnesium, conductivity, and total dissolved solids (TDS) in the samples taken from groundwater and sachet water (that is, drinking water bought from vendors but produced in the communities) were below their respective limits values.

The presence of contaminants can alter the appearance, odour, and taste of water. The organoleptic properties of the water samples indicated that the groundwater sources in the area might not contain decomposed or suspended matter, colloidal substances, or chemical

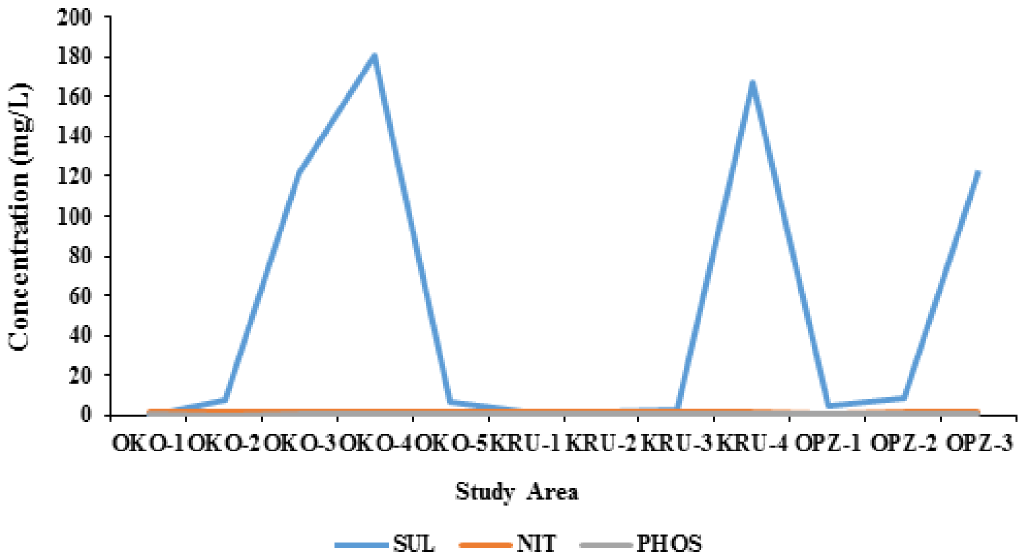

Figure 3. Nutrient concentrations in different water samples.
Source: Authors

contaminants.

Locals typically consider drinking water with unpleasant organoleptic qualities even when these waters are not safe for consumption (Afonne et al., 2020; Morales et al., 2020), because they do not have alternatives. Residual chlorine was high in all the sample locations and was above permissible limits. Although cyanide concentration was below the WHO set limits (WHO, 2011; 2017), its presence is an indication of industrial activities in the area. With crude oil pipelines crisscrossing the area and moving oil exploration platforms littering the waterways, there is a high possibility of large spills of cyanide and chlorinated compounds which would end up in drinking water sources (Glotov et al., 2018; Pérez-Vidal et al., 2020; Sam et al., 2017). Cyanide is a potentially toxic compound and is a fast-acting poison that can be lethal (Manoj et al., 2020). Thus, coastal communities consuming cyanide contaminated water are exposed to potential human health risk. The different water samples from the river indicated hardness due to the presence of a variety of heavy metals and minerals in them. This corroborates the findings of Afonne et al. (2020) and Eyankware et al. (2020), and would lead to scale formation on boilers, poor lather formation, and mineral build-up on equipment. The results in all the stations indicated levels of nitrates, phosphates and sulphates although they were within the permissible limit set by WHO (Table 3 and Figure 3). Significant sources of nitrate include chemical fertilizers, decayed vegetation, animal matter and domestic effluents (Adesakin et al., 2020). Phosphate concentrations ranging from 0.41 to 0.63 mg/L from all the water sources could be attributed to human and animal sewage, agricultural run-off, chemical and fertilizer manufacturing, and detergents. As described earlier, open defecation is a common practice in the area, and could have contributed to levels of phosphate (Ugada and Momoh, 2022). Similarly, the presence of sulphate ranging from 0.33 to 181 mg/L could be attributed to mineral dissolution, atmospheric deposition and other anthropogenic sources (for example, mining, fertilizer, oil and gas exploration and production), which are associated with the study area. However, these activities did not elevate the concentration of sulphate above the WHO guideline of 250 mg/L. WHO reported that excess nitrate concentration in drinking water is considered hazardous for infants because it reduces nitrite in the intestinal tract causing methaemoglobinaemia, and result in abortion in pregnant women (WHO, 2003; Sherris et al., 2021). Although phosphate is not harmful to humans, excessive intake and accumulation may lead to ill-health. Digestive problems could occur from extreme levels of phosphate. Infants are sensitive to sulphate than adults, leading to diarrhoea and dehydration. Nitrates and phosphates are limiting nutrients for the proliferation of eutrophication and harmful algal growth leading to ecosystem degradation.

In aquatic ecosystems, spatial variations exist with respect to physical, chemical, and biological characteristics, thus the relevance of ecosystem monitoring. The survival, composition, diversity, behaviour, and physiology of aquatic organisms are influenced by dissolved oxygen (Onyena et al., 2021).

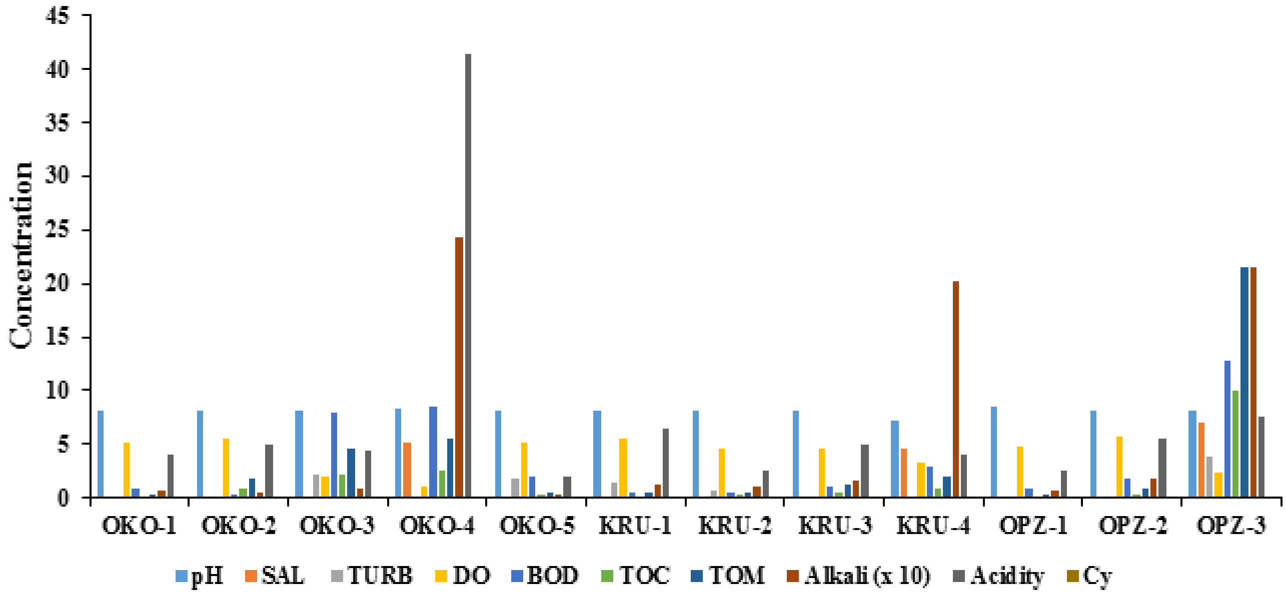

Figure 4. Spatial changes in the physicochemical properties in the water samples.
Source: Authors

Dissolved oxygen levels in all study stations ranged from 1.03 to 5.72 mg/L (Table 3) and the mean dissolved oxygen value of 4.14±1.59 mg/L, was less than the WHO standard of 6 mg/L. Dissolved oxygen (DO) plays a significant role in biological processes and is one of the most important indicators of good water quality and it is a critical parameter for survival of fish and other aquatic organisms (Amakiri et al., 2022). High DO levels in drinking water indicate a better taste than areas with lower DO levels, however, it can damage industrial components, including corrosion in water pipes. High BOD was recorded in samples from the river (OKO-4, OPZ-3) and well water (OKO-3). A high BOD is connected to a low DO, which puts aquatic organisms under stress. The mean BOD value of 3.3±4.09mg/L could be attributed to the high organic compounds in the effluent discharged into the river and the high concentration of aerobic bacteria that biodegrade the wastes (Adesakin et al., 2020). The increase in the BOD levels in the study stations and that of the well water source (OKO-3) indicates the presence of aquatic plants, which decreases the amount of DO through photosynthesis. Study stations OKO-3, OKO-4 and OPZ-3, recorded TOC concentrations higher than the permissible limits (Figure 4). Increased carbon or organic content increases the rate of oxygen utilization. A high organic content means an increase in the growth of microorganisms which contributes to oxygen depletion. Comparatively, the stations with highest TOC levels also recorded increasing BOD values. WHO established that turbidity of drinking water should not be more than 5 NTU and should ideally be less than 1 NTU. Most of the water samples in this study recorded 0 NTU, except for OKO-3, 4, 5, KRU-1, and OPZ-3 whose values were higher than 1 NTU. The turbidity levels across the sampled stretch were low compared to the range of 0.10–500.00 NTU and 0.04–310.00 NTU obtained by Omo-Irabor et al. (2008) in groundwater and surface water, respectively, from western Niger Delta, Nigeria, and Onyena et al. (2021) who recorded 18.5 NTU from a surface water creek around the present study area. High turbidity in a water source can harbor microbial pathogens, which could be deleterious, thus creating health risks to inhabitants who consume water from these sources either directly or indirectly.

Zn, Cr, Cu, and Pb concentrations were below the detection limit, while Al, Ni, Cd, and Fe concentrations were above the respective WHO guideline values in some of the sample stations (Table 2). Nickel concentrations were above the WHO guideline value in all the surface water samples (rivers) and the groundwater samples (boreholes and sachet water) except in OKO-5 (rainwater). It is important to note that the common source of drinking water, either sachet or unpackaged in the study area is the borehole. Aluminium concentrations in the water in the study area are below the detection limit (ND) except for OPZ-1 and OPZ-3. Specifically, OPZ-3, a surface water source, recorded Aluminium concentration (0.369 mg/L) above the WHO guideline value of 0.2 mg/L. Cadmium concentrations were found in both

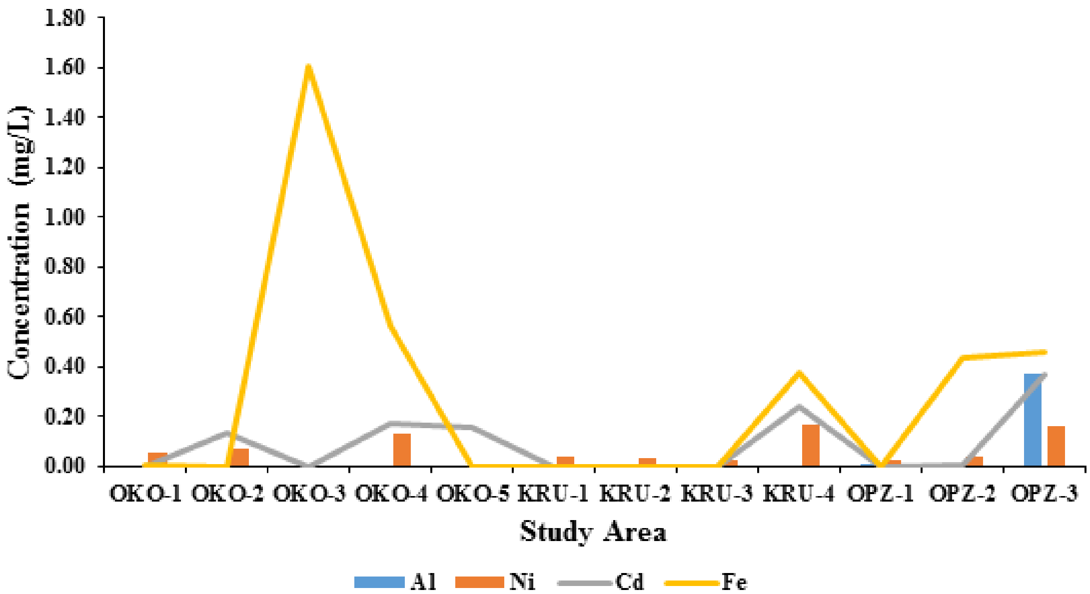

Figure 5. Heavy metal concentrations in different water samples.
Source: Authors.

surface and groundwater sources, with more of the surface waters being contaminated than the groundwater. While cadmium significantly originates from hydrocarbon exploration and extraction, the dumping of mixed wastes containing batteries, and electronic waste, and the discharge of substances including paints, pigments and phosphate fertilizers into surface waters constitute to cadmium levels in the water bodies. Cadmium bioaccumulates in water and is considered toxic to aquatic life and humans. It has an impact on fish endocrine function and behaviour, which could impact breeding and fish population. Also, cadmium exposure lowers bone density and composition and poses cancer risk. Children exposed to cadmium are therefore more vulnerable due to their rapidly growing bones (MPCA, 2014). Cadmium poisoning can be caused by low and high doses and short-term to long exposures (ATSDR, 2012). Iron concentrations were also recorded but not detected in all the water from Kurutie community. Fe, Cd, and Ni concentrations were above the permissible limit set by WHO (Figure 5). The high concentrations of heavy metals in the water samples could be attributed to oil exploration activities in the area. Also, waste water discharge, run-offs, refuse dumps and agricultural activities may have contributed to elevated levels of hydrocarbon, given that the sample stations and the surrounding communities are predominantly islanded with no substantial and good waste management schemes. The rainy season, in which the samples were collected, and the topography of the area are also important factors that could contribute to the contamination of the water samples (Chen and Lu, 2014).

Water Quality Index (WQI)

The overall water quality of the study area was measured (Table 4). The results indicated sample stations are of water quality Class E and are unsuitable for consumption. Although groundwater sources indicated lesser quality (WQI= 139 to 758), surface water recorded a higher WQI of up to 4413. The two water sources are still unsuitable for human consumption as the WQI > 100. The WQI presents parameters in formats that can be understood by all stakeholders. The WQI values recorded in the study area are similar to other Niger Delta ecosystems and confirm the possible presence of contaminants in large quantities (Etim et al., 2013; Nwankwoala and Amachree, 2020; Onyena et al., 2022). The contaminants that affected the WQI could include the presence of heavy metals (Ni, Fe, and Cd), residual chlorine, TDS, conductivity, acidity and hardness that were above WHO set limits.

Geo-accumulation index (Igeo)

The result of the accumulation index is presented in Table 5. The concentration of heavy metals in Station OKO-1 was uncontaminated (Class 1) by any heavy metal studied. The concentration of Ni and Cd in Station

Table 4. Water quality index.

Parameter	OKO-1	OKO-2	OKO-3	OKO-4	OKO-5	KRU-1	KRU-2	KRU-3	KRU-4	OPZ-1	OPZ-2	OPZ-3
W/TEMP	0.006089	0.006089	0.006089	0.0060886	0.006089	0.006089	0.006089	0.006089	0.0060886	0.006089	0.006089	0.0060886
pH	0.039769	0.039379	0.039574	0.0401582	0.039915	0.039866	0.039817	0.039866	0.0347065	0.041132	0.040012	0.0394281
Alkalinity	6.59E-06	5.28E-06	9.23E-06	0.0002374	2.64E-06	1.32E-05	1.06E-05	1.58E-05	0.0001983	6.59E-06	1.85E-05	0.000211
Acidity	0.019471	0.024582	0.021953	0.2015213	0.010125	0.03164	0.012364	0.024338	0.0197627	0.012169	0.02687	0.0369943
Cl	208.1998	390.5152	129.9842	41679.342	65.27344	325.8045	286.4154	273.4732	32563.569	195.2576	652.7344	39074.032
Mg	0.000422	0.000704	0.00422	0.2603215	0.00127	0.002814	0.001407	0.002814	0.0703378	0.001407	0.001127	0.2582401
Hardness	1.33E-05	3.86E-05	3.82E-05	0.0019315	7.17E-06	2.39E-05	2.49E-05	2.32E-05	0.002208	3.6E-05	3.93E-05	0.0022255
COND.	4.8E-06	1.39E-05	1.38E-05	0.0006978	2.59E-06	8.65E-06	9E-06	8.37E-06	0.0007976	1.3E-05	1.42E-05	0.000804
TDS	2.4E-05	6.96E-05	6.89E-05	0.0034888	1.29E-05	4.33E-05	4.5E-05	4.19E-05	0.0039882	6.51E-05	7.1E-05	0.0040198
TURB	0	0	0.030808	0.016459	0.025322	0.020257	0.008722	0	0	0	0	0.0555668
DO	0.04992	0.054121	0.018757	0.0100622	0.050116	0.054903	0.044645	0.044254	0.031652	0.04699	0.055879	0.0238367
BOD	0.033997	0.016021	0.31144	0.3301967	0.077372	0.016803	0.016803	0.042984	0.1129312	0.033215	0.072292	0.5001796
NIT	0.000255	0.000272	0.000304	0.0003292	0.000245	0.000269	0.000232	0.000283	0.000294	0.00018	0.000255	0.0002757
SUL	1.86E-06	4.31E-05	0.000681	0.0010185	3.7E-05	1.11E-05	9.23E-06	1.39E-05	0.0009397	2.95E-05	4.63E-05	0.0006809
PHOS	0.043082	0.036048	0.051874	0.0483572	0.053633	0.053633	0.048357	0.049236	0.055391	0.050995	0.046599	0.0422027
TOC	0.010551	0.072096	0.185516	0.2224432	0.021101	0.019343	0.024618	0.048357	0.0844053	0.01143	0.036927	0.8774635
TOM	2.27E-06	1.55E-05	3.99E-05	4.783E-05	4.54E-06	4.16E-06	5.29E-06	1.04E-05	1.815E-05	2.46E-06	7.94E-06	0.0001887
Cy	0	0	1.688106	2.5321593	0.562702	0	0.562702	0.422027	0	0	0	1.4067552
Al	0	0	0	0	0	0	0	0	0	0.070338	0	3.2443291
Ni	49.23643	58.90787	0	117.81575	12.30911	33.41044	29.01433	24.61822	150.34696	21.10133	32.53121	138.91707
Cd	0	1899.119	0	2377.4162	2208.606	0	0	0	3362.1449	0	70.33776	5190.9266
Fe	0.023446	0	6.271783	2.1921935	0	0	0	0	1.4692776	0	1.703737	1.7897052
Total WQI	**257.66**	**2348.79**	**138.62**	**44180.43**	**2287.04**	**359.46**	**316.20**	**298.77**	**36077.95**	**216.63**	**757.59**	**44412.16**

WQI values	Rating of water quality	Grade	
0 - 25	Excellent	A	**Total WQ1>100**
26 - 50	Good	B	**Class E**
51 - 75	Poor	C	
76 - 100	Very poor	D	
Above 100	Unsuitable water quality	E	

*salinity was omitted. No ideal permissible standard for salinity.
Source: Authors.

Table 5. Geo-accumulation index.

HM	OKO-1	OKO-2	OKO-3	OKO-4	OKO-5	KRU-1	KRU-2	KRU-3	KRU-4	OPZ-1	OPZ-2	OPZ-3
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-5.229	0.000	0.299
Ni	0.900	1.159*	0.000	2.159*	-1.100	0.341	0.138	-0.100	2.511*	-0.322	0.303	2.397*
Cd	0.000	4.170*	0.000	4.494*	4.388*	0.000	0.000	0.000	4.994*	0.000	-0.585	5.621*
Fe	-6.229	0.000	1.835*	0.318	0.000	0.000	0.000	0.000	-0.259	0.000	-0.046	0.025

Classification of Geo Accumulation Index (GAI)

Index class	Igeo Value	Level of contamination classification
0	Igeo<0	Uncontaminated
1	0<Igeo<1	Uncontaminated to moderately contaminated
2	1<Igeo<2	Moderately contaminated
3	2<Igeo<3	Moderately to heavily contaminated
4	3<Igeo<4	Heavily contaminated
5	4<Igeo<5	Heavily to extremely contaminated
6	Igeo>5	Extremely contaminated

*contaminated.
Source: Authors.

OKO-2 revealed a moderate contamination (Class 2), while OKO-3 was only moderately contaminated with Fe (Class 2). Station OKO-4 was moderately contaminated with Ni, but the station with OKO-5 was heavily and extremely contaminated with Cd. However, groundwater sources, including KRU-1, KRU-2, and KRU-3, were uncontaminated to moderately contaminated with either AL, Ni, Cd or Fe. KRU-4 surface water was moderate to heavily contaminated with Ni, whereas the station was heavy to extremely contaminated with Cd. OPZ-3 was extremely contaminated (Class 6) with Cd, while OPZ-1 and OPZ-2 were moderately and heavily contaminated with Ni, Fe and Al concentrations. Heavy metal constituents are an important ecological and health factor for water suitability, species requirements, and ecosystem protection (Achary et al., 2017). The assessment of the geo-accumulation index of the surface and groundwater in the study area reveals the level of each heavy metal examined. The status of Ni and Cd in the water raises concerns, as the regions are currently impacted by heavy metal contamination. While cadmium compounds are known to cause protracted ecotoxicity and human health effects (ATSDR, 2012), nickel exposure can cause allergies, dermatitis, cardiovascular and kidney conditions, pulmonary fibrosis, and lung and nose cancer (USEPA, 2000; Genchi et al., 2020). Ni toxicity affects multiple trophic levels and all aquatic organisms (Wang et al., 2020; Gauthier et al., 2021). There is a possible elevation in the concentration of heavy metals and other persistent organic pollutants since the area still faces serious pollution from different anthropogenic sources from illegal refining, waste dumping, open defecation, and plastic litter.

Nemerow Pollution Index (NPI)

According to the NPI study (Table 6), different water quality parameters studied in the different water sources are potential contributory factors to the degraded water quality, hence the unsuitable WQI. Physicochemical parameters such as acidity, residual chlorine, magnesium, hardness, conductivity, BOD, TOC, nickel, cadmium and iron were the significant parameters that contributed to water pollution across all water sources. However, nickel and residual chlorine were the two most significant parameters in abundance in at least one groundwater and surface water sources.

Most of the groundwater sources in this study indicated that it was majorly nickel and residual chlorine that contributed to water contamination (Table 6). Nickel is released into the environment by power and industrial plants, crude oil extraction, agricultural wastes, run-offs or mobilization from natural deposits in rocks and soils to groundwater. Nickel concentration may irritate the skin, and exposure can cause cancer to the lungs, stomach, and kidneys (Mahurpawar, 2015; Ramirez et al., 2017; Sah et al., 2019). Nickel has also been linked to greenhouse gas emissions and habitat destruction (Han et al., 2021). Residual chlorine constitutes an important safeguard against the risk of subsequent microbial contamination after water treatment, and could be a significant benefit for public health. However, an excessive amount of it in water could be toxic and lead to stomach aches, vomiting, diarrhoea, and dry and itchy skin in humans (Health line, 2018). Nickel concentration in this study ranged from 0.014 mg/L to 0.171 mg/L, exceeding the maximum permissible limit of 0.02 mg/L,

Table 6. Nemerow pollution index.

Parameter	OKO-1	OKO-2	OKO-3	OKO-4	OKO-5	KRU-1	KRU-2	KRU-3	KRU-4	OPZ-1	OPZ-2	OPZ-3
pH	0.961	0.952	0.956	0.971	0.965	0.964	0.962	0.964	0.839	0.994	0.967	0.953
Alkalinity	0.011	0.009	0.016	0.405	0.005	0.023	0.018	0.027	0.338	0.011	0.032	0.360
Acidity	0.471	0.594	0.531	4.871	0.245	0.765	0.299	0.588	0.478	0.294	0.649	0.894
Cl	148.000	277.600	92.400	29628.000	46.400	231.600	203.600	194.400	23148.000	138.800	464.000	27776.000
Mg	0.084	0.140	0.840	51.814	0.253	0.560	0.280	0.560	14.000	0.280	0.224	51.400
Hardness	0.016	0.047	0.046	2.334	0.009	0.029	0.030	0.028	2.668	0.044	0.048	2.689
COND.	0.034	0.099	0.098	4.960	0.018	0.062	0.064	0.060	5.670	0.093	0.101	5.715
TDS	0.068	0.198	0.196	9.920	0.037	0.123	0.128	0.119	11.340	0.185	0.202	11.430
TURB	0.000	0.000	0.438	0.000	0.360	0.288	0.124	0.000	0.000	0.000	0.000	0.790
DO	0.852	0.923	0.320	0.172	0.855	0.937	0.762	0.755	0.540	0.802	0.953	0.407
BOD	0.290	0.137	2.657	2.817	0.660	0.143	0.143	0.367	0.963	0.283	0.617	4.267
NIT	0.036	0.039	0.043	0.047	0.035	0.038	0.033	0.040	0.042	0.026	0.036	0.039
SUL	0.001	0.031	0.484	0.724	0.026	0.008	0.007	0.010	0.668	0.021	0.033	0.484
PHOS	0.245	0.205	0.295	0.275	0.305	0.305	0.275	0.280	0.315	0.290	0.265	0.240
TOC	0.060	0.410	1.055	1.265	0.120	0.110	0.140	0.275	0.480	0.065	0.210	4.990
TOM	0.001	0.009	0.023	0.027	0.003	0.002	0.003	0.006	0.010	0.001	0.005	0.107
Cy	0.000	0.000	0.240	0.360	0.080	0.000	0.080	0.060	0.000	0.000	0.000	0.200
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.000	1.845
Ni	2.800	3.350	0.000	6.700	0.700	1.900	1.650	1.400	8.550	1.200	1.850	7.900
Cd	0.000	27.000	0.000	33.800	31.400	0.000	0.000	0.000	47.800	0.000	1.000	73.800
Fe	0.020	0.000	5.350	1.870	0.000	0.000	0.000	0.000	1.253	0.000	1.453	1.527

NPI values≤= 1: Low minute quantity to significantly cause water degradation

NP1 values > 1: indicates presence of parameters significantly cause water degradation

Source: Authors.

while the residual chlorine ranged from 11.6 mg/L to 7407 mg/L and has maximum permissible limit of 0.25 mg/L (Table 3); and thus, could pose risk to locals consuming water from the sampled area. Although cadmium concentrations were not detected in most groundwater sources, they were found in surface and rain water ranging from 0.005 mg/L to 0.369 mg/L. Cadmium was observed as a contributory parameter to water contamination beside residual chlorine and Ni in OKO-2, OKO-4 and OKO-5. The roofing sheets of the buildings where rainwater was collected were made up of asbestos and covered by soot, resulting in faintly dark water. Cadmium concentration in ground water sources OKO-2, OKO-5 and OPZ-2, as well as surface water OKO-4, KRU-4 and OPZ-3 indicated the impacts of flared gas in the area. The cadmium concentration ranged from0.005 to0.369 mg/L (Table 3). The WHO permissible level for Cd is 0.005 mg/L. The local population drink water from these cadmium-contaminated sources, especially during water scarcity, as there are no alternative water supplies. A striking observation and health concern from the results is the presence of Cd in a minute quantity (0.005 mg/L) in a major treated tap water source in OKO- 2 and OPZ 2; a major source of drinking water supplying many households including the Nigeria Maritime University. It is necessary to conduct additional research on the source of cadmium in tap water to provide detail evidence for decision-making. Ni and Cd contributed significantly to the heavy metals load in the water samples than all other metals analysed. They were also responsible for the high levels of the pollution indices obtained from the NPI in the water sources.

The results from the NPI indicated the presence of a battery of chemical contaminants in the surface water OKO-4 and OPZ-3 and thus are prone to ecological and health risks to aquatic lives and humans. According to the NPI result (Table 6) acidity, residual chlorine, TDS, conductivity, hardness, Ni, Cd and Fe parameters measured in samples from stations OKO-4 and OPZ-3 (surface water) showed that they contributed to the poor water quality. Table 3 also illustrated that these contributing parameters that resulted to that the poor water quality were found to be above the permissible limits of WHO. For all the water sources, the NPI revealed that residual chlorine and with at least one heavy metal included a major factor that resulted in the extensive unsuitability of the water sources, the nutrients, cyanide, turbidity, pH, and TOM recorded less quantities to assign them as significant cause of water contamination or unsuitability, The assessment indicated that the surface waters were more polluted than the groundwater samples, and could be attributed to the daily discharge of effluents, agrochemicals, run-offs and hydrocarbon into surface waters. Increasing levels of toxic metals in drinking water sources poses significant risk to human health and other receptors, as they penetrate the food chain (Achary et al., 2017). For example, high levels of Al as reported in the samples could result in neurodegenerative diseases in humans (Bondy and Campbell, 2017). A significant outcome of this study is that contamination levels are higher in rivers compared to boreholes and sachets in the overall water quality assessment. This could be attributed to the open nature of rivers and other surface waters to anthropogenic sources. Surface waters are primary receivers of run-offs which deliver mixed refuse (Singh et al., 2016), even as they serve as direct dumps for refuse, sewage, oil spills (Ite et al., 2018), illegal refining waste, bunkering, and domestic wastewater. For the groundwater sources, in addition to seepage from surface water, contamination may be caused by geogenic activities such as weathering and leaching of minerals from rocks (Afonne et al., 2020). Singh et al. (2016) reported that poor waste disposal systems can contaminate water systems since leachates from municipal solid waste landfills contain high concentrations of heavy metals and metalloids. According to Kapoor and Singh (2021), metals are transported by run-off from industrial effluents and other chemicals into water sources if there is no adequate treatment. The study area has major industries and pipelines with poor waste disposal and drainage systems, coupled with their agricultural activities in which chemicals are used to improve crop yields, without appropriate regulation.

Principal component analysis (PCA) was applied to explain the experiential interrelationship of cluster parameters in simple patterns, as expressed in the nature of correlations between the parameters (Figure 6). PCA 1 recorded 61.04 % and PC 2 recorded 13.23 % variations. Figure 6 shows the biplot of the PCA, and the proximity of lines for pair of parameters denotes the strength and nature of their reciprocated relationship. Conductivity, acidity, alkalinity, TDS, and nutrients studied showed an equal influence and a weak negative correlation with each other (PC 2). However, Cd, Fe, Cy, and Mg in PC 2 indicated a weak positive influence on the component and point to the importance of mineral dissolution, chemical weathering, and erosion of earth particles. PC 2 was also weakly and positively associated with pH but insignificantly influenced by dissolved oxygen. PC 2 loaded significantly for parameters including phosphate and PC 1 for nitrate, and such loadings represent agricultural activities (use of fertilisers and agrochemicals). OKO-1 to 3 and 5, as well as KRU 1 to 3 and OPZ 1 and 2, exhibited a weak positive effect on PC 2. OKO-4 and KRU-4, surface waters showed a strong negative influence, although OPZ-3, which is also surface water, remained a strong positive influence in PC 2 (Figure 6). Turbidity, TOM, TOC, BOD and Al exhibited a weak positive correlation with each other (PC 1) which could be associated with factors of chemical compound disassociation to ions, climate variability, and organic pollution. All study stations were strongly and negatively loaded in PC 1 except for OKO-3, OKO-4, KRU-4, and OPZ-3. OKO-4, KRU-4, and OPZ-3 demonstrated a strong positive influence in PC 1, but OKO-3 showed a weak positive influence.

Conclusion

Most drinking water sources in the sampled communities are contaminated with organic and metallic contaminants. The surface water was heavily polluted with Ni, Cd, Fe, residual chlorine, TDS, conductivity, acidity and magnesium compared with the groundwater and sachet water sources. WQI results indicated that all sampled waters exceeded the critical WQI value of 100. This could expose the communities to significant public health issues including immune suppression, cancer, reproductive failure and acute poisoning, if urgent measures are not taken. While there is need to control sources of contamination, particularly the oil mining and illegal refining industries, governments at the local and

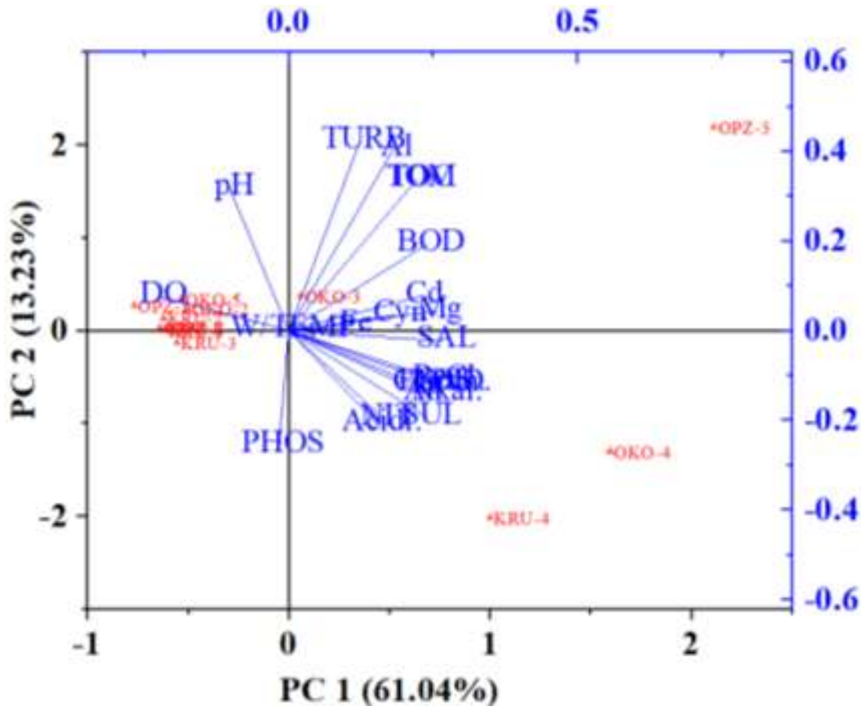

Figure 6. Principal Component Analysis (PCA) of the physicochemical characteristics in water from study location.
Source: Authors

state levels should urgently provide potable drinking water for these coastal communities. A multi-agency collaboration involving the state environmental protection agency, the water resources ministry, the sanitation agency, and the waste management parastatals is needed to develop and implement a framework that would protect water resources, enhance communities' access to potable drinking water, and manage waste sustainably.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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