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Groundwater Quality Assessment in Crude Oil-Impacted Communities in Ogoniland in the Niger Delta Using the Water Quality Index (WQI)

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Abstract*: Crude oil pollution has resulted in severe groundwater pollution in Ogoniland in the Niger Delta. There are indications that groundwater pollution extends beyond pollution sites, justifying the need for this comprehensive groundwater quality study. This study assessed the groundwater quality in crude oil-impacted communities in Ogoniland in the Niger Delta using the Water Quality Index (WQI). Forty-two groundwater samples were collected from fourteen wells in Ogoniland and analyzed using standard methods. The physical and chemical water quality parameters which include temperature, electrical conductivity (EC), turbidity, total dissolved solids (TDS), pH, total alkalinity, hardness, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, sulphate, phosphate, chloride, heavy and essential metals were determined. Total coliform counts were determined using the standard microbiological pollution indicators assessment method. The overall quality of the groundwater samples and their suitability for human consumption were determined using the weighted arithmetic WQI. Nemerow Pollution Index (NPI) was used to identify the polluting parameters in the groundwater. The results obtained showed that the studied groundwater had physical, chemical and microbial contaminations. The WQI results were above 100 (Class E) for all the samples and ranged from 282.76 in S9 to 467.29 in S3, indicating that all the studied samples were unsuitable for drinking. NPI results showed that the parameters that contributed most to the deteriorated groundwater status include turbidity, BOD, COD, phosphate, chloride, cadmium, iron, and total coliform bacterial load. Recommendations include detailed groundwater characterization in Ogoniland and an improved groundwater remediation approach that considers a combination of *in-situ* and *ex-situ* groundwater remediation options to ensure effective decontamination of polluted groundwater in Ogoniland.

***Keywords*: bioremediation, groundwater, water quality index, water quality parameters, pollution.**

1. Introduction

The Niger Delta region in Nigeria is home to one of the largest wetland ecosystems in the world and is a significant source of oil and gas for the Nigerian economy [1]. However, years of oil exploration, production, and transportation in the region including Ogoniland have resulted in severe environmental degradation, including groundwater pollution [2]. The contamination of groundwater in Ogoniland has led to the release of toxic substances into the environment, including crude oil, benzene, toluene, ethylbenzene, and xylene [3]. Consequently, it has resulted in the degradation of aquatic and terrestrial ecosystems, loss of biodiversity, and significant public health concerns [4]. The affected communities have reported cases of skin irritation, respiratory illnesses, cancers, and other chronic diseases [5], [6]. Efforts to address groundwater pollution in Ogoniland have been slow and ineffective [7]. While the ongoing remediation efforts in Ogoniland suffer some setbacks [8], there are indications of groundwater pollution in locations beyond the polluted sites indicating a bigger problem, thus justifying the urgent need for a comprehensive groundwater quality assessment using the Water Quality Index (WQI). WQI is a tool used to measure and report on the overall quality of water in a particular area [9]. It is a mathematical tool that combines multiple water quality parameters to produce a single number or score that can be used to evaluate the suitability of water for various uses, thus turning complex water quality data into information that is understandable and usable by the public [10], [11]. The weighted arithmetic WQI is typically expressed on a scale of 0 to 100; a score of 0 indicates that the water is of good quality and suitable for all uses, while a score of 100 and above indicates that the water is highly polluted and not suitable for any use [12]-[14]. This study aimed to assess the quality of groundwater in crude oil-impacted communities in Ogoniland in the Niger Delta using the water quality index (WQI) and Nemerow Pollution Index (NPI) and to suggest a better strategy for effective and holistic groundwater remediation in Ogoniland.

2. Materials and Methods

A total of sixty groundwater samples were collected from fourteen wells and six boreholes in Ogoniland and analyzed using standard American Public Health Association-prescribed methods. The physicochemical and microbial water quality parameters which include temperature, electrical conductivity (EC), turbidity, total dissolved solids (TDS), pH, total

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alkalinity, hardness, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, sulphate, phosphate, chloride, heavy and essential metals (magnesium, aluminium, lead, copper, nickel, zinc, cadmium, chromium, and iron) and total coliform were determined. The physical groundwater quality parameters such as temperature, electrical conductivity (EC), turbidity and total dissolved solids (TDS) were determined in the triplicate samples collected from 20 locations in the study area. Temperature, EC and turbidity were analysed using a multi-parametric probe (Horiba Water Checker Model, U10). TDS was analysed using the evaporation method (APHA method 2540 C). Chemical parameters were analysed using standard methods. DO was analysed using Winkler's method while BOD and COD were analysed using the ultimate BOD test and titrimetric methods respectively. Nitrate was analysed using the sodium salicylate method; hardness was determined using the Ethylenediaminetetraacetic acid (EDTA) titrimetric method; sulphates and phosphates were analysed using spectrophotometric methods. The concentrations of magnesium, aluminium, lead, copper, nickel, zinc, cadmium, chromium and iron were determined by spectrophotometric methods after digestion and acidification with 0.5% nitric acid at a pH of 2.0. Coliform bacteria counts were determined by incubating serially diluted samples in a test tube containing lactose broth with inverted Durham tubes at 37°C for 24 to 48 hours. After the incubation, the tubes which produced gas were counted and the numbers were compared with the most probable number (MPN) table.

A. Weighted Arithmetic Water Quality Index (WAWQI) calculation

The water quality index (WQI) was determined using the following set of equations for the Weighted Arithmetic WQI method (WAWQI):

$$WQI = \frac{\sum Qiwi}{\sum wi} \tag{1}$$

$$\text{Quality Score, Qi} = \frac{Vi - vo}{Si - vo}\, x\, 100 \tag{2}$$

$$\text{Unit weight (for each parameter, wi} = \frac{k}{Si} \tag{3}$$

$$\text{The proportionality constant, k} = \frac{1}{\sum \frac{1}{Si}} \tag{4}$$

where:

- vi = expected concentration of the nth parameter
- v_0 = optimal value of the evaluated water parameter in a sample of normal water (Usually zero except pH of 7.0 and DO of 14 mg/l).
- si = standard value specified for the nth parameter (WHO 2011 and 2017 for drinking water quality).

The classification of the index ranges from 0 to 100 (Excellent to unsuitable water quality) depending on the values scored. The classification is summarised in Table 1, established in standard methods for classifying water quality based on the WAWQI method.

Table 1
The weighted arithmetic water quality index (WAWQI) water quality rating

WQI	Water quality status	Grade
0 – 25	Excellent	A
26 – 50	Good	B
51 – 75	Poor	C
76 – 100	Very poor	D
Above 100	Unsuitable for drinking	E

Source: [13], [14], [15]

B. Determination of Nemerow Pollution Index (NPI)

The Nemerow Pollution Index which determines the total pollutant level and considers the properties of the analysed groundwater samples was calculated using the following equation.

$$\text{NPI} = \frac{\text{Cn}}{\text{Sn}} \tag{5}$$

where Cn = concentration of the nth parameter, Sn = prescribed maximum values of the nth parameter. In the interpretation, [NPI ≤ 1] implies that the parameters are of minimal concentration whereas [NPI>1] implies that parameters are in excessive concentration and constitute pollution.

Table 2
WQI calculation for the groundwater samples

S.No.	Parameter	Si	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
1	pH	8.5	4.917	4.223	4.467	3.800	5.060	4.633	4.897	4.217	4.497	4.527	3.090	4.767	4.233	4.733
2	Temperature	28	25.767	26.177	26.020	26.077	26.400	26.533	27.067	28.823	25.910	26.013	26.303	26.200	26.447	26.433
3	Total alkalinity	600	0.237	0.457	1.033	0.253	2.403	0.000	1.463	0.000	1.783	3.740	1.033	5.000	3.343	4.820
4	Turbidity (NTU)	5	8.467	6.633	6.833	7.733	14.267	8.267	16.823	7.567	13.833	14.867	6.333	9.833	6.233	20.220
5	Hardness (mg/L)	425	19.633	14.367	21.513	14.500	29.133	5.667	33.527	4.667	38.833	41.133	19.490	55.870	58.067	37.770
6	TDS (mg/L)	1000	147.333	6.300	334.667	3.667	24.667	2.667	15.333	1.333	16.000	16.280	314.667	46.333	37.567	19.667
7	Electrical Conductivity (uS/cm)	2500	290.333	11.667	671.000	7.667	47.333	3.000	32.333	2.667	30.667	31.967	631.667	94.333	72.667	34.667
8	Dissolve Oxygen (mg/L)	6	3.153	1.917	1.833	1.800	2.077	4.107	2.017	2.210	0.897	0.853	1.183	1.847	1.520	5.667
9	BOD (mg/L)	3	11.333	5.333	1.837	5.267	11.767	1.897	10.467	1.447	2.440	4.530	1.580	3.627	1.333	13.517
10	COD (mg/L)	10	20.633	10.767	5.190	13.667	20.800	5.367	18.633	5.557	8.487	9.670	5.053	4.443	3.347	22.510
11	Nitrate (mg/L)	50	2.333	0.370	2.793	1.507	0.910	0.120	3.920	0.037	1.720	3.287	2.577	2.887	2.163	7.057
12	Sulphate (mg/L)	250	11.000	0.000	0.000	1.347	0.000	0.000	0.540	0.000	0.000	0.000	0.000	0.000	0.000	2.813
13	Phosphate (mg/L)	2	0.327	1.647	2.937	2.717	4.560	1.713	18.800	0.983	3.217	3.610	2.513	3.063	2.183	20.303
14	Chloride (mg/L)	0.25	25.667	1.867	6.833	1.803	0.000	0.000	0.903	0.000	1.103	2.133	6.700	5.123	3.427	4.100
15	Magnesium (mg/L)	150	0.127	0.147	0.151	0.529	0.147	0.203	0.028	0.182	0.127	0.159	0.158	0.202	0.148	3.074
16	Aluminium (mg/L)	0.2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	Lead (mg/L)	10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	Copper (mg/L)	2000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	Nickel (mg/L)	0.02	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	Zinc (mg/L)	3000	0.108	0.014	0.305	0.019	0.000	0.162	0.032	0.160	0.057	0.034	0.269	0.046	0.042	0.045
21	Cadmium (mg/L)	0.005	0.014	0.019	0.028	0.019	0.022	0.027	0.021	0.021	0.018	0.020	0.016	0.018	0.021	0.023
22	Chromium (mg/L)	50	0.000	0.000	0.000	0.192	0.766	0.000	0.078	0.000	0.000	0.000	0.000	0.000	0.000	1.013
23	Iron (mg/L)	0.3	0.000	0.125	0.286	0.281	0.012	0.587	0.329	0.584	0.391	0.294	0.298	0.375	0.417	1.483
24	Total Coliform (cfu/100ml)	10	0.000	0.000	0.000	0.000	927.333	14.667	13.667	13.333	280.333	295.667	0.000	0.000	0.000	15.333
k			0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038	0.0038
∑Qiwi			368.365	295.164	467.293	295.550	333.060	417.006	322.578	320.951	282.762	319.101	289.701	311.003	335.996	377.416
∑wi			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
WQI			368.37	295.16	467.29	295.55	333.06	417.01	322.58	320.95	282.76	319.10	289.70	311.00	336.00	377.42

3. Result

The results obtained showed that the studied groundwater had physical, chemical and microbial contaminations. The WQI result showed deteriorated water quality. A summary of the results of the WQI of the fourteen locations in Ogoniland is presented in Table 2. The WQI of the studied groundwater samples ranged from 282.76 in S9 to 467.29 in S3; the WQI values are all above 100 and reveal that all the studied locations have groundwater that is within Grade E indicating that they are unfit for drinking.

Table 3
Summary of WQI of groundwater samples from Ogoniland

Sample	Community	WQI	Water quality status
S1	Ogale	368.37	Unfit for drinking
S2	Alueken	295.16	Unfit for drinking
S3	Alueken	467.29	Unfit for drinking
S4	Ogale	295.55	Unfit for drinking
S5	Nsisioken	333.06	Unfit for drinking
S6	Nsisioken	417.01	Unfit for drinking
S7	Nsieta	322.58	Unfit for drinking
S8	Nsieta	320.95	Unfit for drinking
S9	Ebubu	282.76	Unfit for drinking
S10	Ebubu	319.10	Unfit for drinking
S11	Alode	289.70	Unfit for drinking
S12	Alode	311.00	Unfit for drinking
S13	Bera	336.00	Unfit for drinking
S14	Bera	377.42	Unfit for drinking

Table 3 shows the summary of the water quality status for the fourteen locations reported. The Nemerow Pollution Index (NPI) was determined for each of the studied water samples to identify the specific contaminants that contributed to the severe pollution of the studied groundwater, making them unfit for drinking. The NPI result is shown in Table 4. The shaded portions of the table show the parameters show the parameters that exceeded the allowable limits (parameter >1). The result shows that the parameters that contributed most to the deteriorated status of the studied groundwater include turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), phosphate, chloride, cadmium, iron, and total coliform bacterial load. NPI for turbidity in S14 is 4.04 implying that turbidity was four times higher than the safe limit in the sample. The NPI for chloride is 102.67 in S1 indicating that chloride pollution in the sample was approximately 103 times higher than the safe limit. The nine listed parameters were higher than their respective allowable limits for drinking water and thus contributed to the unsafe water quality as determined by the WQI, all of which fell within Grade E showing that they were unfit for drinking.

4. Discussion

The result obtained from this study shows that all the sixty samples collected exhibited physical, chemical, and microbial contamination, raising concerns about the overall groundwater quality in the study area. All the groundwater samples were acidic. The mean pH levels of the samples ranged from 3.090 in S11 to 5.060 in S5 indicating acidic groundwater. Acidity leads to elevated levels of dissolved metals in groundwater, which can be harmful to both ecosystems and human health [16]. For instance, elevated levels of cadmium were detected in the groundwater samples, and they are all above the allowable limit of 0.005 mg/L according to the World Health Organization (WHO) standard for drinking water. Increased acidity of groundwater can mobilise heavy metals in the soil, making them more bioavailable and potentially toxic to plants and microbial communities [17], since the mobility of metals in water is a function of pH especially as acidic conditions enhance the propensity of metals to be mobilized in solution [18]. Alkalinity levels display significant variability. Locations like S11 and S12 exhibit extremely low alkalinity (0 mg/L), indicating minimal buffering capacity against further acidification. Conversely, S5 and S13 have considerably higher total alkalinity levels (2.40 mg/L and 3.34 mg/L, respectively.

Table 4
Nemerow Pollution Index (NPI) of the studied groundwater samples

	Parameters	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
1	pH	0.58	0.50	0.53	0.45	0.60	0.55	0.58	0.50	0.53	0.53	0.36	0.56	0.50	0.56
2	Temperature	0.92	0.93	0.93	0.93	0.94	0.95	0.97	1.03	0.93	0.93	0.94	0.94	0.94	0.94
3	Total alkalinity	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.01
4	Turbidity (NTU)	1.69	1.33	1.37	1.55	2.85	1.65	3.36	1.51	2.77	2.97	1.27	1.97	1.25	4.04
5	Hardness (mg/L)	0.05	0.03	0.05	0.03	0.07	0.01	0.08	0.01	0.09	0.10	0.05	0.13	0.14	0.09
6	TDS (mg/L)	0.15	0.01	0.33	0.00	0.02	0.00	0.02	0.00	0.02	0.02	0.31	0.05	0.04	0.02
7	Electrical Conductivity (uS/cm)	0.12	0.00	0.27	0.00	0.02	0.00	0.01	0.00	0.01	0.01	0.25	0.04	0.03	0.01
8	Dissolve Oxygen (mg/L)	0.53	0.32	0.31	0.30	0.35	0.68	0.34	0.37	0.15	0.14	0.20	0.31	0.25	0.94
9	BOD (mg/L)	3.78	1.78	0.61	1.76	3.92	0.63	3.49	0.48	0.81	1.51	0.53	1.21	0.44	4.51
10	COD (mg/L)	2.06	1.08	0.52	1.37	2.08	0.54	1.86	0.56	0.85	0.97	0.51	0.44	0.33	2.25
11	Nitrate (mg/L)	0.05	0.01	0.06	0.03	0.02	0.00	0.08	0.00	0.03	0.07	0.05	0.06	0.04	0.14
12	Sulphate (mg/L)	0.04	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
13	Phosphate (mg/L)	0.16	0.82	1.47	1.36	2.28	0.86	9.40	0.49	1.61	1.81	1.26	1.53	1.09	10.15
14	Chloride (mg/L)	102.67	7.47	27.33	7.21	0.00	0.00	3.61	0.00	4.41	8.53	26.80	20.49	13.71	16.40
15	Magnesium (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
16	Aluminum (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	Lead (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	Copper (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	Nickel (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20	Zinc (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
21	Cadmium (mg/L)	2.80	3.73	5.60	3.73	4.33	5.47	4.13	4.20	3.60	4.00	3.27	3.67	4.13	4.53
22	Chromium (mg/L)	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
23	Iron (mg/L)	0.00	0.42	0.95	0.94	0.04	1.96	1.10	1.95	1.30	0.98	0.99	1.25	1.39	4.94
24	Total Coliform (cfu/100ml)	0.00	0.00	0.00	0.00	92.73	1.47	1.37	1.33	28.03	29.57	0.00	0.00	0.00	1.53

Shaded areas indicate above-limit parameters and the number of times they are above the allowable limit

WQI is often used for the recognition and analysis of groundwater quality and determination of water pollution status [19], and can be considered as the representation of the combined impact of various water quality variables on the overall water quality [20]. The ecological status of water can be assessed using the WQI value produced using the WAWQI method procedure. The weighted arithmetic WQI value increases in mathematical proportion with the decreasing water quality. A low value of the WQI indicates good water quality, whilst higher values indicate poor quality, with values above 100 denoting water quality that is unfit for drinking [21]. The WQI results showed that all the samples had WQI values above 100 (Grade E) and therefore unsuitable for drinking. The estimated WQI for the fourteen locations ranges from 183.19 in S18 to 282.76 in S9. These values show that the groundwater in these locations is very polluted and needs urgent attention and remediation. WQI has remained a valuable tool for determining and communicating the overall quality of groundwater without necessarily mentioning the various parameters. Several researchers have reported similar groundwater WQI values within the oil-rich Niger Delta indicating strong groundwater pollution that renders it unsuitable for drinking [22]-[28].

The Nemerow Pollution Index (NPI) analysis revealed the main polluting parameters responsible for the high WQI values of groundwater samples from the study area. NPI is another effective means of assessing and communicating detailed water quality [29]. The NPI result showed that several key contaminants emerged as significant contributors to the unfit-for-drinking status [30]. These include high turbidity levels indicating the presence of suspended solids, potentially providing a breeding ground for pathogens and hindering disinfection processes [31]; elevated BOD and COD, suggesting high levels of organic matter decomposition, potentially depleting oxygen crucial for aquatic life and impacting water quality [30]-[32], excessively high phosphate concentrations, posing a threat of eutrophication [33], [34], elevated chloride levels, with the potential to impact on the taste of the groundwater and also a trigger for pipe corrosion [35]. The presence of heavy metals such as cadmium and iron, alongside high total coliform bacteria further raises concerns about potential health risks associated with consuming the contaminated water [36]-[38]. The people who reside in the study area solely depend on this groundwater for drinking. This result further emphasizes the need for urgent emergency measures that include effective groundwater remediation in the area. Detailed groundwater characterization in Ogoniland is highly recommended. It is also recommended that a combination of both *in-situ* and *ex-situ* groundwater remediation options be considered in Ogoniland to ensure holistic and effective decontamination of polluted groundwater since it is evident that pollution has spread beyond polluted sites.

References

[1] Verlecar X. N., Desai S. R., Sarcar A. and Dalal S. G. Water Res. 40. 2006. 3304. Dike, S, Toby, B. And Steven, A (2021). Amnesty Programme, Enabling Laws and Sustainable Development in Niger Delta of Nigeria. International Journal of Social Sciences, 7, 57-74.

[2] Enyoghasim, M. O, Anochiwa, L, Agbanike, F. T, Uwazie, I. U, Kalu, E. U, Onwuka, O. K. And Ogbonnaya, I. O (2019). Oil exploration and exploitation in Nigeria and the challenge of sustainable development: an assessment of the Niger Delta. International Journal of Energy Economics and Policy, 9(4): 369-380.

[3] Amakama, N. J, Knapp, C. W, Raimi, M. O. And Nimlang, N. H (2021). Environmental fate of toxic volatile organics from oil spills in the Niger Delta Region, Nigeria. International Journal of Environment, Engineering and Education, 3(3):89-101.

[4] Precious, P. and Akujuru, V (2021). Impact of Loss of Water Supply in Ogoni Land as A Result of Oil Exploration and Production. American Journal of Humanities and Social Sciences Research, 5(11):211-219.

[5] Yakubu, O. H (2017). Particle (soot) pollution in Port Harcourt Rivers State, Nigeria—double air pollution burden? Understanding and tackling potential environmental public health impacts. Environments, 5(1): 2.

[6] Ite, A. E, Harry, T. A, Obadimu, C. O, Asuaiko, E. R. And Inim, I. J (2018). Petroleum hydrocarbons contamination of surface water and groundwater in the Niger Delta region of Nigeria. Journal of Environment Pollution and Human Health, 6(2): 51-61.

[7] Ezugwu, B. U, Bala, J. D, Abioye, O. P. And Oyewole, O. A. (2022). Effects of Petroleum Pollution and the Remediation Attempts in Ogoniland, Rivers State, Nigeria: A Review. Nigerian Journal of Microbiology, 36(1): 6081-6101.

[8] Sam, K, Zabbey, N. and Onyena, A. P (2022). Implementing contaminated land remediation in Nigeria: insights from the Ogoni remediation project. *Land use policy*, *115*, 106051.

[9] Banda, T. D. and Kumarasamy, M. V (2020). Development of Water Quality Indices (WQIs): A Review. *Polish Journal of Environmental Studies*, 29(3).

[10] Adelagun, R. O. A, Etim, E. E. And Godwin, O. E (2021). Application of water quality index for the assessment of water from different sources in Nigeria. Promising techniques for wastewater treatment and water quality assessment, 267, 25.

[11] Manna, A, and Biswas, D (2023). Assessment of drinking water quality using water quality index: a review. *Water Conservation Science and Engineering*, *8*(1), 6.

[12] Fang, Y, Zheng, T, Zheng, X, Peng, H, Wang, H, Xin, J. And Zhang, B (2020). Assessment of the hydrodynamics role for groundwater quality using an integration of GIS, water quality index and multivariate statistical techniques. Journal of Environmental Management, 273, 111185.

[13] Chatterji C. and Raziuddin, M. (2002). Determination of water quality index (WQI) of a degraded river in Asanil industrial area, Ranigunj, Burdwan, west Bengal. Nature, Environment and Pollution Technology, 1(2):181-189.

[14] Shweta, T, Bhavtosh, S, Prashant, S. And Rajendra, D (2013). Water Quality Assessment in Terms of Water Quality Index. American Journal of Water Resources, 1 (3): 34-38.

[15] Brown R. M, McCleiland, N. J, Deiniger, R. A. and O'Connor, M. F. A (1972). Water quality index – crossing the physical barrier, (Jenkis, S.H. ed.): *Proceedings in International Conference on water pollution Research, Jerusalem*, 6,787-797.

[16] Liu, Y, Wei, L. And Wu, Q (2023). Impact of acid mine drainage on groundwater hydrogeochemistry at a pyrite mine (South China): a study using stable isotopes and multivariate statistical analyses. Environ Geochem Health, 45, 771-785.

[17] Barra Caracciolo, A. And Terenzi, V (2021). Rhizosphere microbial communities and heavy metals. Microorganisms, 9(7):1462.

[18] Amadi, A. N, Olasehinde, P. I, Yisa, J, Okosun, E. A, Nwankwoala, H. O. And Alkali, Y. B (2012). "Geostatistical Assessment of Groundwater Quality from Coastal Aquifers of Eastern Niger Delta, Nigeria". Geosciences, 2(3): 51-59.

[19] Patel, D. D, Mehta, D. J, Azamathulla, H. M, Shaikh, M. M, Jha, S. And Rathnayake, U (2023). Application of the weighted arithmetic water quality index in assessing groundwater quality: A case study of the South Gujarat region. Water, 15(19): 3512.

[20] Ghoderao, S. B, Meshram, S. G. And Meshram, C. Development and evaluation of a water quality index for groundwater quality assessment in parts of Jabalpur District, Madhya Pradesh, India. Water Supply, 2022(22) 6002-6012.

[21] Teshome, F. B (2020). Seasonal water quality index and suitability of the water body to designated uses at the eastern catchment of Lake Hawassa. *Environmental science and pollution research*, *27*, 279-290.

[22] Wilson, N. L, Ezekwe, I. C. And Chukwu-Okeah, G. O (2021). Surface and Ground Water Quality Determination in Orashi and Sombreiro River Basin using Weighted Arithmetic Water Quality Index. Journal of Research in Environmental and Earth Sciences, 7(8): 47-54.

[23] Amadi, A. N. Udoh, B. O. Ozoji, T. M. Akande, W. G. Shaibu, I. Dan-Hassan, M. A. And Oguntade, A. S (2020). Quality Assessment of Groundwater in Parts of Niger Delta, Southern Nigeria using Metal Pollution Index and Factor Analysis. Environmental Science, 15(2): 8-20.

[24] Nwankwoala, H. O. And Amachree, T (2020). The water quality index (WQI) and hydrochemical characterization of groundwater resources in hydrocarbon-polluted sites in the Niger Delta. Journal of Mining and Geology, 56(1): 69-84.

[25] Iloba, K. I, Akawo, N. O, Adamu, K. M., Ohwojeheri, O. R. And Edafiogho, M. A (2022). Assessment of Groundwater Drinking Sources in Eku and Its Environs, in the Niger-Delta Region of Nigeria. Baghdad Science Journal, 19(6):1219-1219.

[26] Emeka, C, Nweke, B, Osere, J. And Ihunwo, C. K (2020). Water quality index for the assessment of selected borehole water quality in Rivers State. European Journal of Environment and Earth Sciences, 1(6).

[27] Ajayi, O. And Okeke, O. C (2024). Assessment of Quality of Surface Water Resources of Kolo Creek and Environs, Niger Delta, Nigeria, using Water Quality Index and Multivariate Statistical Analysis. Scholarly Journal of Science and Technology Research and Development, 3(1): 101-138.

[28] Amah, V. E. And Agu, F. A (2020). Geostatistical modelling of groundwater quality at Rumuola community, Port Harcourt, Nigeria. Asian Journal of Environmental Ecology, 12(1):37-47.

[29] Singh, S, Kumara, S. and Kumar, V (2021). Analysis of groundwater quality of haridwar region by application of Nemerow Pollution Index method. *Indian Journal of Ecology*, *48*(4), 1149-1154.

[30] Sawyer, C. N, McCarty, P. L. and Parkin, G. F (2003). Chemistry for environmental engineering and science. 5th edition, McGraw-Hill, New York, USA, pp. 768.

[31] Maguvu, T. E, Bezuidenhout, C. C, Kritzinger, R, Tsholo, K, Plaatjie, M, Molale-Tom, L. G. and Coertze, R. D (2020). Combining physicochemical properties and microbiome data to evaluate the water quality of South African drinking water production plants. *PLoS One*, *15*(8), e0237335.

[32] Koda, E, Miszkowska, A. and Sieczka, A (2017). Levels of organic pollution indicators in groundwater at the old landfill and waste management site. *Applied Sciences*, *7*(6), 638.

[33] Mishra, R. K. (2023). The effect of eutrophication on drinking water. *British Journal of Multidisciplinary and Advanced Studies*, *4*(1), 7-20.

[34] Schilling, K. E., Jacobson, P. J., St. Clair, M., & Jones, C. S. (2020). *Dissolved phosphate concentrations in Iowa shallow groundwater*, vol. 49, no. 4, pp. 909-920.

[35] Mahidashti, Z, Rezaei, M. and Asfia, M. P (2020). Internal under-deposit corrosion of X60 pipeline steel upon installation in a chloride-containing soil environment. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *602*, 125120.

[36] Mahajan, M, Gupta, P. K, Singh, A, Vaish, B, Singh, P, Kothari, R. and Singh, R. P (2022). A comprehensive study on aquatic chemistry, health risk and remediation techniques of cadmium in groundwater. *Science of The Total Environment*, *818*, 151784.

[37] Adeyemi, A. A. and Ojekunle, Z. O (2021). Concentrations and health risk assessment of industrial heavy metals pollution in groundwater in Ogun state, Nigeria. *Scientific African*, *11*, e00666.

[38] Sarkar, B, Mitchell, E, Frisbie, S, Grigg, L, Adhikari, S. and Maskey-Byanju, R (2022). Drinking water quality and public health in the Kathmandu Valley, Nepal: coliform bacteria, chemical contaminants, and health status of consumers. *Journal of Environmental and Public Health*, *2022*(1), 3895859.