https://chemclassjournal.com/
ChemClass Journal Vol. 9 Issue 4 (2025); 129 - 146
e-ISSN:3092-8214 p-ISSN:3092-8206
doi.org/10.33003/chemclass-2025-0904/10

Physicochemical Characteristics and Health Risk Assessment of Toxic Elements in Surface Water of Ataba Creek, Rivers State, Nigeria

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Abstract

The contamination of aquatic environments by toxic elements is a growing concern worldwide due to its severe implications for ecological health and human well-being. Anthropogenic activities and uncontrolled processes degrade water quality. Early detection of threats from contaminated water can protect all aspects of life and habitat degradation. This study is aimed to assess some Physicochemical parameters of surface water (pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), and salinity), and to estimate the health risk levels of some toxic elements, (As, Ni, Cr, Pb and Cd) in the water samples of geolocated areas of Ataba Creek by Egwe-Osot Village. Samples were collected along its banks at Up, middle and downstream from November, 2024 to February, 2025. The physicochemical parameters were analyzed using multiparameter meter (HACH 1520), while toxic elements were determined using standard method of aqua regia digestion followed by atomic absorption spectrophotometer (AAS). Different models and water ecological risks were utilized for assessment. The results revealed that the water quality parameters, pH, temperature, EC, TDS, and salinity, were within acceptable limits recommended by the USEPA (2018), at all locations, except for the elevated levels of toxic elements. cadmium (1.53 mg/kg), lead (1.19 mg/kg), and chromium (0.46 mg/kg) at downstream exceeded the USEPA limits of 0.005, 0.015 , and 0.10 mg/kg respectively, confirming the anthropogenic influence on water quality. Water quality index value greater than 100 (14 times) indicates water is unsuitable for domestic use. Pollution load index >> 1 reflects significant to severe pollution. The non-carcinogenic, HI values for both adults and children far exceed the safe threshold (HI ≥ 1), indicating significant non-carcinogenic risks across all sampling points, especially downstream. The high carcinogenic risk (CR) values, mainly driven by **cadmium, chromium, and nickel** exceeded acceptable risk levels (**CR > 10^{-4}**), necessitating **urgent intervention** to mitigate further exposure and protect public health.

Keywords: Assessment, water quality, concentration, health risk, toxic metals, Ataba creek.

Introduction

The contamination of aquatic environments by toxic elements is a growing concern worldwide due to its severe implications for ecological health and human well-being [1]. These elements, including toxic elements such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), originate from both natural and anthropogenic

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sources, accumulating in water bodies, sediments, and aquatic organisms [2]. Rivers serve as critical resources for domestic, industrial, and agricultural purposes; however, their exposure to pollutants compromises water quality, aquatic biodiversity, and human health [3]. The Ataba stretch of the Bonny River in Rivers State, Nigeria, is a vital water body supporting fisheries, agriculture, and local livelihoods. However, it is increasingly threatened by industrial discharges, oil exploration, and domestic waste pollution [4]. Due to their non-biodegradable nature, toxic elements persist in the environment, posing significant risks to human populations through direct consumption of contaminated water and seafood [5].

Consequently, understanding the levels, distribution, and potential risks of these contaminants in the Ataba stretch of the Bonny River is essential for environmental management and public health protection [1].

Industrial activities in the Niger Delta region, including oil exploration and artisanal refining, contribute significantly to heavy metal pollution in aquatic ecosystems [2]. Crude oil spills, gas flaring, and discharge of untreated effluents introduce metals such as vanadium (V), nickel (Ni), and lead (Pb) into surface waters [3]. The health risks associated with prolonged exposure to toxic elements include renal impairment, developmental toxicity in children, cardiovascular diseases, and increased cancer risks [4].

Previous studies have documented varying concentrations of PTEs in the Niger Delta's aquatic ecosystems, highlighting the need for continuous monitoring and risk assessment [6]. However, specific data on the Ataba stretch of the Bonny River remain limited. Given the socio-economic importance of the river and its role in sustaining local fisheries, agriculture, and domestic water use, there is an urgent need for a comprehensive health risk assessment of toxic elements in this region [1]. Also, of recent, there has been reported cases of communicable diseases such as typhoid, cholera and skin diseases traceable to the quality of water in Rivers State, and no information on the levels and distribution of toxic elements in Ataba River, there is a need to carryout health risk assessment of toxic elements in Ataba River. This study therefore, aims to determine the levels of physicochemical characteristics and assess the health risk of toxic elements in surface water, from the Ataba stretch of Bonny River. The Ataba River in Andoni Local Government serves as a major source of domestic water, food, and livelihood for the local population. However, its quality is increasingly threatened by diverse anthropogenic activities. These include industrial effluent discharge, agricultural runoff, domestic waste disposal, and oil exploration and extraction. The findings will provide scientific evidence to guide policy decisions, enhance water resource management, and protect public health from the adverse effects of heavy metal pollution [2].

Materials and Methods

Study Area

Ataba is a coastal town in Andoni, Rivers State, Nigeria. The town is known for abundant coconut and palm kernel shells [6].

It is a western end of Andoni. Over the years Ataba has been a receptacle of multiple migrations. Geographical coordinates: Latitude 4.65ºN - 4.85ºN, Longitude 7.35ºE - 7.55ºE (Fig. 1) [7]. River Network: Ataba River is a tributary of Bonny River, with a length of approximately 50 km. Low-lying coastal plain with numerous creeks and mangrove swamps. Elevation: 5-10 meters above sea level.

Sample Collection

Water samples were collected along the Ataba River. A total of nine (9) water samples were collected consecutively for three (3) months from November, 2024 to January, 2025. The coordinates of the sampling locations were taken with the use of Geographic Positioning System (GPS), Garmin Channel 78 Model. All sample containers for water sample collection were rinsed with the water being sampled before putting the sample into the containers. The water samples were collected with the aid of a stainless-steel surface water sampler. Samples for physicochemical parameters were collected in 1 L plastic containers. Water samples for toxic elements analyses were collected in plastic vials and fixed with 2% nitric acid to preserve the integrity of the samples before taking them to the laboratory for analyses. All the laboratory tests were carried out at ambient laboratory temperature, which were recorded. All measurements were done in triplicates and the average values recorded.

All equipment and instruments were calibrated prior to use for quality assurance in order to ascertain the accuracy of the results obtained.



Fig.1: Map of the Study area

Data Analysis

Water Quality Index

The assessment of hand-dug wells using the Water Quality Index (WQI) provides an integrative view of their suitability for drinking purposes.

WQI = ∑ Wi Qi /∑Wi

Where;

WQI= Water quality index

i = Unit weightage

Wi = Unit Weightage

Qi = Sub index of ith parameter, Qi = Vn/Sn *100

Where Vn = Concentration of ith parameters

Wi = K/Sn

K = 1/∑ (1/Sn)

Where;

Sn = Recommended Standard for ith parameter

Contamination factor and Pollution load index

Contamination factor (CF) is calculated as the ratio between the measured levels of metal content and the reference of the metal, indicates the metal enrichment in that system. In the present study, if CF > 1 for a particular metal, contamination exists; if CF≤1, there is no metal enrichment of natural or human activity source in that system.

$$CF = \frac{\text{Concentration of metal}}{\text{Reference value of the metal}}$$

The CF value is a measure of contamination potential of each metal. In order to determine the metal pollution potential of a sampling location, pollution load index (PLI) can be estimated. This is determined as the nth root of the product of the n CFs,

$$PLI = (CF_1 \times CF2 \times CF_3 \times \ldots\ldots\ldots\ldots CF_n)^{1/n}$$

When *PLI* > 1, pollution is considered to be present, whereas if PLI < 1, no pollution is assumed.

Also, the degree of contamination (C_d) can be determined by summing up the *CF* values. The C_d values indicate the contamination of the environment as follows:

$C_d < 8$, low degree of contamination

$8 < C_d < 16$, moderate degree of contamination

$16 < C_d < 32$, considerable degree of contamination

$32 < C_d$, very high degree of contamination.

Heavy metal pollution index (HPI)

Heavy metal pollution index (HPI) serves as an indicator for assessing the comprehensive water quality with regard to heavy metals. The HPI model that was used in the present study;

$$HPI = \frac{\sum_{i=1}^{n} WiQi}{\sum_{i=1}^{n} Wi} \quad (1)$$

where Qi=sub index of the i th parameters; Wi=unit weightage of i th parameter; n=number of parameters considered. Parameter sun index Qi is calculated by;

$$Qi = \sum_{i=0}^{n} \frac{\{Mi(-)Ii\}}{(Si - Ii)} \times 100 \quad (2)$$

where Mi=heavy metal monitored value of i th parameter, Ii=ideal value of i th parameter, and Si=standard value of i th parameter. Water pollution indices can be customized for different purposes, but the HPI in this study focuses specifically on heavy metal contamination in drinking water. While the established critical limit for HPI in drinking water is typically 100 [8], a modified three-tier scale was opted that was based on Edet & Offiong (2002) [9]. This categorizes HPI values into low risk (30), with more understanding of potential health concerns related to heavy metal intake through drinking water.

Health Risk Assessment

The non-carcinogenic risk associated with consumption of groundwater which is contaminated with metals was calculated according to the guidelines of US Environmental Protection Agency (USEPA 2005) [10]. The risk for children and adults was separately evaluated using the function:

$$CDI = \frac{C_W \times IRW \times EF \times ED}{BW \times AT} \quad (3)$$

where CDI represents the Chronic Daily Intake or exposure dose (mg/kg/day), Cw represents the contaminant concentration in water (mg/L), IRW denotes the ingestion rate (for adults IRW is 2 L/day while for children it is 1 L/day), EF denotes the Exposure Frequency (equivalent to 365 days/ year), ED is the exposure duration (for adults and children, ED is 70 and 6 years, respectively), BW represents the body weight (for adults and children, BW is 70 and 15 kg,

respectively), AT represents the average exposure time (AT for adults is 25,550 days while for children, it is 2190 days) [11, 12, 13]. To evaluate the non-carcinogenic risk imposed by individual elements, the hazard quotient (HQ) as outlined by Li et al. (2016) [14] and Zhang et al. (2018) [15] was calculated as follows:

$$HQ = \frac{CDI}{RfD} \quad (4)$$

where RfD signifies the reference dose of a specific element (mg/kg/day). According to Duggal et al. (2017) and Barzegar et al. (2018b), RfD for different elements is equivalent to 0.7 (Fe), 1 (Al), 0.3 (Zn), 0.046 (Mn), 0.0035 (Pb), 0.02 (Ni), 0.0003 (As), 0.2 (Ba) and 0.04 (Cu) [12,13]. Finally, to calculate the hazard index (HI) of the water samples, the summation of HQ values for the elements is computed, i.e.,

$$HI = \sum HQ \quad (5)$$

Values of HI and HQ greater than 1 indicate the noncarcinogenic risk of the specific element exceeds the limit of acceptance (HI=1), while values less than 1 indicate that the non-carcinogenic risk is within limits of acceptance [16, 17].

Results and Discussion

The result of the physicochemical parameters and heavy metal levels of surface water of geolocated sessions of Ataba Rivers is presented in Table 1 with USEPA (2018) limits of some parameters listed. The figures 1 to 6 displayed the visual bar chart representations of the physicochemical parameters and toxic elements as presented in Table 1 for comparison. The consecutive figures 1 to 6 are the pH, Temperature, Electrical conductivity, Total dissolved solids, Salinity and Heavy metal levels at up

(Usw), middle (Msw) and down (Dsw) stream sections of Ataba River. Table 2 presented the water quality index of the surface water at upstream, middle and downstream respectively. The water quality indices (WQIs) at the three stations were greater than 100. Table 3 is evaluated output of the degree of contamination (Cd) of heavy metal ranging from 32 to 166. Table 4 is pollution load index ranging from 5 to 713. Table 5 is heavy metal assessment index having values ranging from 37 to 170. The Tables in 6 and 7 are calculated non-carcinogenic health risk assessment by ingestion and dermal route exposure of both adult and children, of the three stations, with respective values ranging from 53 to 225 and 107 to 450 by ingestion and 107 to 450 and 907 to 3728 for dermal of the two age group categories. Table 8 is carcinogenic human health risk assessment by ingestion having levels from 4.3×10^{-2} to 1.1×10^{-2} in adult and 8.5×10^{-2} to 2.2×10^{-2} in children.

Table 1: Mean and Standard Deviation of Measured Surface Water Parameters

Locations	Upstream		Midstream		Downstream		USEPA
Parameters	Mean	Stdev	Mean	Stdev	Mean	Stdev	(2018)
pH	7.54	± 0.36	7.40	± 0.48	7.48	± 0.29	6.5-8.5
Temperature (°C)	30.40	± 1.36	30.20	± 1.55	30.27	± 1.53	-
EC (µs/cm)	34.83	± 3.65	35.10	± 3.48	34.77	± 4.18	-
TDS (ppt)	17.20	± 1.80	17.47	± 1.66	17.40	± 1.85	-
Salinity (‰)	2.04	± 0.23	2.07	± 0.21	2.07	± 0.24	-
Cadmium (mg/kg)	0.33	± 0.03	0.23	± 0.08	1.53	± 0.56	0.005
Lead (mg/kg)	0.24	± 0.08	1.19	± 0.47	1.15	± 0.17	0.015
Chromim (mg/kg)	0.36	± 0.21	0.24	± 0.18	0.46	± 0.37	0.10
Arsenic (mg/kg)	0.01	± 0.00	0.06	± 0.02	0.05	± 0.02	0.01
Nickel (mg/kg)	0.69	± 0.27	0.03	± 0.01	0.46	± 0.37	0.10

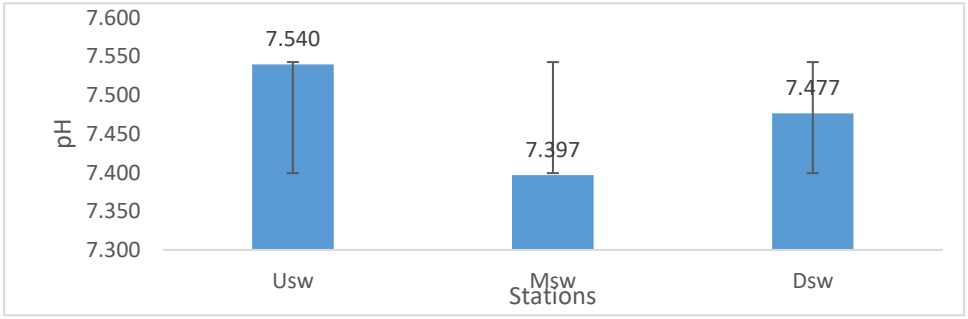


Fig.1: pH of up (Usw), middle (Msw) and down (Dsw) stream section at Ataba River

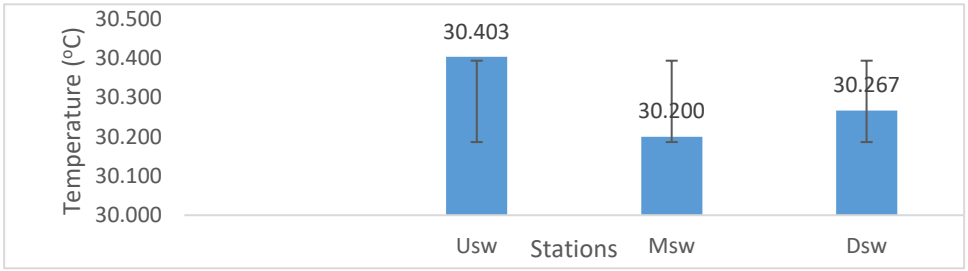


Fig..2: Temperature of up (Usw), middle (Msw) and down (Dsw) stream section at Ataba River

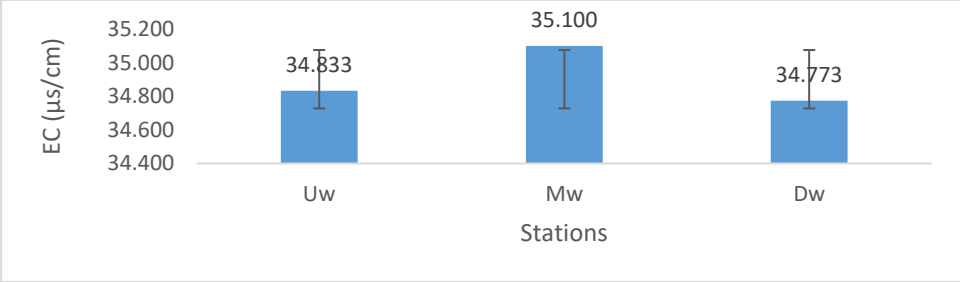


Fig..3: Electrical conductivity of up (Usw), middle (Msw) and down (Dsw) stream section at Ataba River

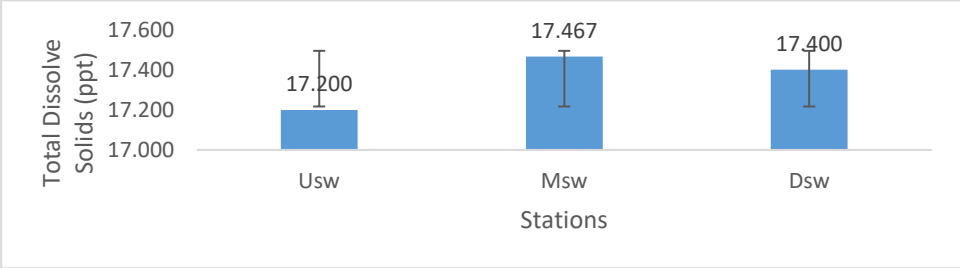


Fig. 4: Total dissolved solids of upper (Usw), middle (Msw) and down (Dsw) stream section at Ataba River

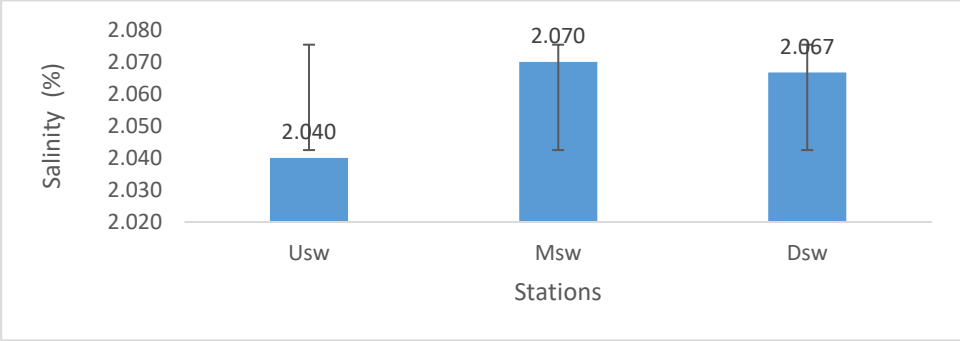


Fig. 5: Salinity of upper (Usw), middle (Msw) and down (Dsw) stream section at Ataba River

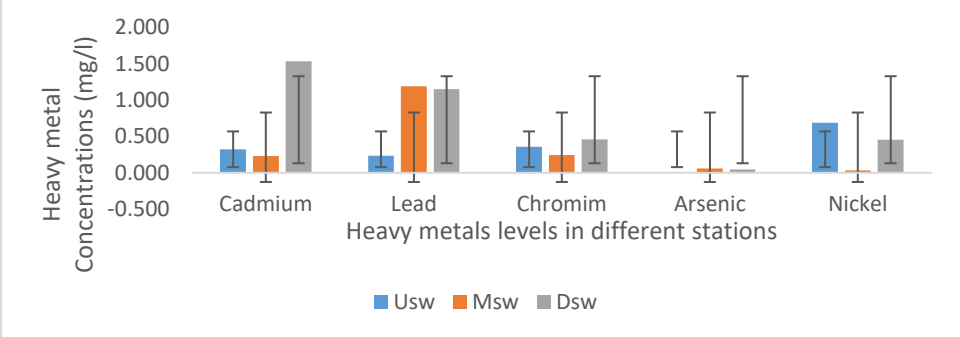


Fig. 6: Heavy metal levels at upper, middle and downstream section of Ataba River

Table 2: Water Quality Index (WQI) of the Surface Water at different location

Locations	**WQI**
Upstream	1588.67
Midstream	1421.72
Downstream	7465.71

Table 3: Degree of Contamination of Heavy Metal (Cd)

	Usw	Msw	Dsw		Usw	Msw	Dsw
Parameter	CAi			Cni	Cfi		
Cadmium	0.325	0.233	1.531	0.01	32.53	23.27	153.13
Lead	0.236	1.189	1.152	0.1	2.36	11.89	11.52
Chromim	0.357	0.245	0.461	0.5	0.71	0.49	0.92
Arsenic	0.011	0.058	0.048	0.01	1.07	5.83	4.80
Nickel	0.691	0.035	0.457	1	0.69	0.03	0.46
				Cd = ∑Cfi	37.37	41.51	170.84

Cd > 3 is high contamination

Table 4: Contamination Factor (CF) and Pollution Load Index of toxic elements (PLI)

Conc. (Ci)	**Usw**	**Msw**	**Dsw**	**Bi**	**CFu**	**CFm**	**CFd**
Cadmium	0.325	0.233	1.531	0.01	32.5333	23.267	153.13
Lead	0.236	1.189	1.152	0.1	2.36	11.887	11.523
Chromium	0.357	0.245	0.461	0.5	0.71467	0.4893	0.9213
Arsenic	0.011	0.058	0.048	0.01	1.06667	5.8333	4.8
Nickel	0.691	0.035	0.457	1	0.69067	0.0347	0.457
				PLI	**8.08484**	**5.4734**	**713.27**

CF <1 – low contamination, 1≤CF<3 – moderate, 3≤CF<6 – considerable, CF>6 – very high

PL1 > 1 – polluted

Table 5: Heavy Metal Assessment Index (HEI) In Surface water

Parameter	WHO (Hmac)	Hc (Usw)	Hc (Msw)	Hc (Dsw)	HEIu	HEIm	HEId
Cadmium	0.01	0.33	0.23	1.53	32.53	23.27	153.13
Lead	0.10	0.24	1.19	1.15	2.36	11.89	11.52
Chromium	0.50	0.36	0.24	0.46	0.71	0.49	0.92
Arsenic	0.01	0.01	0.06	0.05	1.07	5.83	4.80
Nickel	1.00	0.69	0.03	0.46	0.69	0.03	0.46
				∑(HEI)=	37.37	41.51	170.84

HEI<10 – low contamination, 10<HEI<20 – medium, HEL>20 - high

Table 6: Non-Carcinogenic Human Health Risk Assessment (HI) by Ingestion

	Hazard Quotient (HQ) Ingestion					
	Adult			Children		
Parameter	Usw	Msw	Dsw	Usw	Msw	Dsw
Cadmium	21.69	15.51	102.09	43.38	31.02	204.18
Lead	21.85	110.06	106.70	43.70	220.12	213.40
Chromim	7.94	5.44	10.24	15.88	10.87	20.47
Arsenic	1.19	6.48	5.33	2.37	12.96	10.67
Nickel	1.15	0.06	0.76	2.30	0.12	1.52
HI=∑HQ	53.82	137.55	225.12	107.64	275.10	450.24

HI > 4 high risk level

Table 7: Non-Carcinogenic Human Health Risk Assessment (HI) by Dermal

	Hazard Quotient (HQ) Dermal					
	Adult			Children		
Parameter	Usw	Msw	Dsw	Usw	Msw	Dsw
Cadmium	16.17	11.57	76.13	650.67	465.33	3062.67
Lead	6.70	33.77	32.74	67.43	339.62	329.24
Chromim	5.92	4.05	7.63	119.11	81.56	153.56
Arsenic	1.77	9.67	7.95	35.56	194.44	160.00
Nickel	0.17	0.01	0.11	34.53	1.73	22.85
HI=∑HQ	30.74	59.06	124.57	907.30	1082.69	3728.31

HI > 4 high risk level

Table 8: Carcinogenic Human Health Risk Assessment (CR) by Ingestion

	CR Adult			CR Children		
Parameter	Usw	Msw	Dsw	Usw	Msw	Dsw
Cadmium	4.1×10^{-3}	2.9×10^{-3}	1.9×10^{-2}	8.2×10^{-3}	5.9×10^{-3}	3.9×10^{-2}
Lead	6.7×10^{-5}	3.4×10^{-4}	3.3×10^{-4}	1.3×10^{-4}	6.7×10^{-4}	6.5×10^{-4}
Chromim	6.0×10^{-3}	4.1×10^{-3}	7.7×10^{-3}	1.2×10^{-3}	8.2×10^{-3}	1.5×10^{-2}
Arsenic	5.3×10^{-4}	2.9×10^{-3}	2.4×10^{-3}	1.1×10^{-3}	5.8×10^{-3}	4.8×10^{-3}
Nickel	1.9×10^{-2}	9.7×10^{-4}	1.3×10^{-2}	3.9×10^{-2}	1.9×10^{-3}	$2.6 \times 10^{-}$
TR=∑CR	3.0×10^{-2}	1.1×10^{-2}	4.3×10^{-2}	6.0×10^{-2}	2.2×10^{-2}	8.5×10^{-2}

$CR<10^{-6}$ – no carcinogenic risk, $CR>10^{-4}$ – higher chance of getting cancer, CR 10^{-6} to 10^{-4} – acceptable risk

Physicochemical Parameters of Surface Water

The water quality parameters, including pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), and salinity, were within acceptable limits recommended by the USEPA (2018), except for the elevated levels of toxic

elements. The pH values across upstream (7.54 ± 0.36), midstream (7.40 ± 0.48), and downstream (7.48 ± 0.29) sites fell within the permissible range of 6.5–8.5, indicating neutral to slightly alkaline conditions conducive to metal solubility and mobility. Temperatures were relatively uniform (~30.2–30.4°C), supporting the physicochemical stability of the aquatic system. EC, TDS, and salinity values showed minor variations, reflecting similar ionic compositions across sites. However, the elevated concentrations of cadmium (up to 1.53 mg/kg), lead (1.19 mg/kg), and chromium (0.46 mg/kg) far exceeded the USEPA limits (0.005 mg/kg for Cd, 0.015 mg/kg for Pb, and 0.10 mg/kg for Cr), confirming the anthropogenic influence on water quality. These exceedances underscore the need for urgent regulatory interventions to mitigate heavy metal discharge into the aquatic system [18].

Water Quality Index of the Surface Water

The Water Quality Index (WQI) is a crucial composite indicator used to assess the overall quality of water by integrating various physicochemical parameters into a single numerical value that simplifies complex data for decision-making and public communication [19]. The Tables 4.2 – 4.4 presented indicates WQI values for three distinct water sources: upstream water (Usw), midstream water (Msw), and downstream water (Dsw), with values of 1588.69, 1421.72, and 7465.71, respectively. Interpretation of these results follows the standard WQI categorization. Typically, a WQI value greater than 100 indicates water that is unsuitable for drinking without extensive treatment [20]. All three sites exceed this threshold by a significant margin, highlighting severe water quality degradation. However, the downstream water (Dsw) presents an exceptionally high WQI value of 7465.71, which is markedly higher than both Usw and Msw, suggesting acute contamination and possibly the cumulative effect of anthropogenic activities along the watercourse. This could include industrial discharges, municipal sewage, and agricultural runoff, all of which typically contribute significantly to downstream pollution [21].

The relatively lower WQI values recorded upstream (1588.69) and midstream (1421.72) still reflect heavily polluted water, but comparatively, they point toward a progressive deterioration in quality as the water flows downstream. This spatial variation underscores the necessity of identifying point and non-point sources of pollution to implement effective watershed management strategies.

Contamination and Pollution Assessment of toxic elements in Surface Water

The contamination factors (CFs) of toxic elements in surface water (Table 4.6) varied across the upstream, midstream, and downstream locations.

The contamination factor (CF) and the degree of contamination (Cd) are critical indices used in

evaluating the anthropogenic impact and ecological risk of heavy metal pollutants in aquatic environments. These indices help to assess the extent of contamination in water bodies and identify potential threats to ecological and human health [22, 23].

The contamination factor (CF) is calculated as the ratio of the measured concentration of a metal in the environment (CAi) to a reference or background concentration (Cni). According to Hakanson (1980), CF is classified into four categories: CF < 1: Low contamination, 1 ≤ CF < 3: Moderate contamination, 3 ≤ CF < 6: Considerable contamination, CF ≥ 6: Very high contamination [22].

Cadmium exhibited very high contamination at all stations: USW (CF = 32.53), MSW (CF = 23.27), and DSW (CF = 153.13). These values far exceed the threshold for severe contamination, indicating intense anthropogenic input likely from industrial, agricultural runoff, and possibly sewage discharge [21]. The downstream (DSW) site, with a CF of 153.13, is especially concerning and suggests heavy contamination accumulation downstream.

Lead showed moderate to considerable contamination: USW (2.36) - moderate, MSW (11.89) and DSW (11.52) - very high contamination. These high values suggest significant lead inputs, possibly from fossil fuel combustion, old piping, or battery and paint industries [24]. The peak CF at MSW indicates localized pollution possibly from midstream anthropogenic activities.

Chromium levels reflected low to moderate contamination: USW (0.71) and MSW (0.49) - low, DSW (0.92) - still within the low contamination range. Although CF values are < 1, the slight elevation towards downstream suggests accumulation or inputs from tanneries or metal industries [25].

Arsenic contamination levels varied: USW (1.07) - moderate, MSW (5.83) and DSW (4.80**)** - considerable contamination. Given the high toxicity of arsenic, even moderate contamination is alarming. The elevated CFs downstream and midstream may point to pesticide application, industrial effluents, or leachates from mining sites [26].

Nickel showed low contamination across all stations: USW (0.69), MSW (0.03), and DSW (0.46).

These low CFs suggest minimal anthropogenic input of nickel or efficient dilution/dispersion in the water column.

The degree of contamination (Cd) is the sum of all individual contamination factors (∑CF). According to Hakanson (1980), Cd values are interpreted as: Cd < 6: Low degree of contamination, 6 ≤ Cd < 12: Moderate, 12 ≤ Cd < 24: Considerable, Cd ≥ 24: Very high degree of contamination [22]. The calculated Cd values were: USW = 37.37, MSW = 41.51 and DSW = 170.84. All sites fall within the very high degree of contamination category, with the downstream site (DSW) showing the most extreme level of contamination. This trend aligns with the cumulative input and transport of pollutants from

upstream to downstream, indicating that hydrological movement and human activities along the watercourse significantly affect contamination distribution [27].

The Pollution Load Index (PLI**)** is a valuable tool for assessing the overall level of heavy metal pollution in an environment, particularly surface water and sediments. It provides a single number that reflects the cumulative contamination status of multiple toxic elements relative to their background levels [28].

The PLI is calculated using the geometric mean of the contamination factors (CF) of various metals: PLI= 1 indicates baseline level of pollutants (no pollution), < 1 suggests no pollution, > 1 implies progressive pollution load, >> 1 reflects significant to severe pollution.

From the Table 4.6, the PLI values for the surface water across stations were: Upstream (USW): 8.08; Midstream (MSW): 5.47 and Downstream (DSW**):** 713.27 and Upstream (USW) – PLI = 8.08 This indicates a very high pollution load at the upstream location. The major contributors are Cadmium (CF = 32.53) and Lead (CF = 2.36), which are far above permissible thresholds, revealing anthropogenic inputs possibly from nearby urban runoff, industrial effluents, or mining activities [21].

Midstream (MSW) is PLI = 5.47. Although slightly lower than upstream, the midstream still exhibits a high pollution load. Elevated contamination is largely due to Cadmium (23.27) and Lead (11.89), suggesting intense midstream contamination sources—perhaps industrial discharge, domestic wastewater, or agricultural runoff [23].

Downstream (DSW) is PLI = 713.27. This exceptionally high PLI reveals a catastrophic level of pollution downstream. The most dominant factor is Cadmium (CF = 153.13**)**, followed by Lead (11.52) and Arsenic (4.80). Such cumulative build-up downstream is characteristic of pollution transport via surface runoff and hydrological flow, which tends to carry and deposit contaminants at lower reaches [25, 27]. This pattern reflects a typical pollution gradient from upstream to downstream.

High PLI values, particularly at DSW, raise serious concerns about ecological toxicity, bioaccumulation in aquatic organisms, and potential risks to human health through water usage or consumption of contaminated fish [29]. The overwhelming dominance of cadmium at all sites—especially downstream—suggests that targeted intervention is urgently required, including source control and regulatory enforcement

HEI Classification is as follows: HEI < 10: Low pollution; 10 ≤ HEI < 20: Medium pollution and HEI ≥ 20: High pollution. Upstream (USW) has HEI = 37.37. This value signifies a high pollution level. Cadmium contributes the largest share (32.53), followed by Lead (2.36). Cadmium's concentration (0.33 mg/L) is 33 times the WHO permissible limit (0.01 mg/L), suggesting an

alarming cadmium influx. Potential sources may include industrial discharges, battery manufacturing, and agricultural runoff [23, 29]. .Midstream (MSW) has HEI = 41.51. This location also falls in the high pollution category, slightly higher than the upstream site. The most significant contributors are again Cadmium (23.27) and Lead (11.89). Notably, Lead concentration (1.19 mg/L) is nearly 12 times higher than the WHO limit. This pattern indicates cumulative input from midstream pollution sources such as waste effluents, urban runoff, and industrial activities [24].

Downstream (DSW) – HEI = 170.84**.** The downstream location exhibits a severely elevated HEI, over four times higher than upstream and midstream. This is indicative of very high pollution. The dominant pollutant is Cadmium (153.13), which is a staggering 153 times higher than WHO permissible levels. This suggests intense downstream accumulation of pollutants transported from upstream and midstream, exacerbated by reduced dilution or settling of metals in stagnant zones [25, 27].

The consistently high HEI across all locations, particularly downstream, indicates serious environmental degradation and potential health hazards for communities that depend on this water for domestic or agricultural purposes. Cadmium and Lead, known for their nephrotoxic and neurotoxic effects, pose the most serious risks [30]. The bioaccumulation of these metals in aquatic organisms also threatens food safety.

Non-Carcinogenic and Carcinogenic Health Risk Assessment of Surface Water

The Non-Carcinogenic Human Health Risk Assessment via ingestion is a critical tool used to evaluate the potential health risks posed by exposure to toxic elements through contaminated water. This assessment uses the Hazard Quotient (HQ) and Hazard Index **(**HI**)** to determine whether exposure levels exceed safe thresholds.

HQ < 1 indicates no significant non-carcinogenic risk, HQ ≥ 1 suggests potential health effects (USEPA, 2002). Hazard Index (HI). The HI is the summation of HQs for multiple metals: HI < 1: Acceptable (no risk), HI ≥ 1: Unacceptable (potential adverse health effects, especially with chronic exposure).

The Non-Carcinogenic Human Health Risk Assessment via dermal exposure evaluates the potential health risks posed by skin contact with contaminated surface water containing toxic elements. Although ingestion is often the dominant route, dermal absorption can also contribute significantly, especially during bathing, swimming, or daily water use—more so in children due to their higher skin surface area-to-body weight ratio and more permeable skin [30, 31].

Non-carcinogenic health risk assessment based on hazard index (HI) showed that both adults and children are at risk via ingestion and dermal exposure routes (Tables 4.8 & 4.9). For ingestion,

the HI values for children (up to 450.24) significantly exceeded the safe threshold of 1, highlighting the susceptibility of younger populations due to physiological differences and higher exposure relative to body weight [32]. Dermal exposure risk was even more alarming in children (up to 3728.31), with cadmium and lead contributing significantly to the overall risk burden. These results are consistent with findings from other polluted aquatic systems where dermal and oral exposures are dominant pathways for metal uptake [32].

The Carcinogenic Risk (CR**)** assessment evaluates the probability of an individual developing cancer over a lifetime as a result of exposure to carcinogenic contaminants through ingestion of contaminated water. This is a critical measure in human health risk assessments, especially for toxic elements like cadmium, lead, chromium (VI), arsenic, and nickel, which are known or probable human carcinogens [32, 33].

Carcinogenic risk (CR) assessment for surface water ingestion revealed total carcinogenic risk (TCR) values of 3.0×10^{-2} (upstream), 1.1×10^{-2} (midstream), and 4.3×10^{-2} (downstream) for adults, and notably higher values for children (up to 8.5×10^{-2}). These exceed the USEPA acceptable risk threshold of 1×10^{-4}, suggesting considerable long-term cancer risk, especially from chromium and cadmium exposure [34 - 38].

Conclusion

The physicochemical parameters fall within acceptable limits, the concentrations of toxic elements greatly exceed USEPA standards, posing serious environmental and public health risks.

The observed WQI values reveal that all sections of the water body assessed are severely polluted, with downstream regions bearing the brunt of water quality degradation. These findings stress the urgent need for remedial actions including pollution control, treatment infrastructure development, and continuous monitoring to restore the ecological integrity of the aquatic system.

The PLI analysis shows that all studied locations suffer from heavy metal pollution, with the severity increasing from midstream to downstream. Cadmium is the principal contaminant across all sites. These findings highlight the need for sustained monitoring, pollution source identification, and remediation effort**s** to safeguard aquatic ecosystems and public health.

The HI values for both adults and children far exceed the safe threshold ($HI \geq 1$), indicating significant non-carcinogenic risks across all sampling points, especially downstream. Children are at an alarming level of health risk, highlighting the urgent need for intervention to prevent potential chronic toxicity.

Recommendations

1. Further work should be carried out on other physicochemical properties of the study area
2. Immediate mitigation efforts: Regulate and treat effluents before discharge.
3. Continuous monitoring: Especially downstream areas where pollution is most severe.
4. Pollution source identification: Trace industries contributing to Cd and Pb load.
5. Public health risk assessment: Especially in communities relying on the water for domestic or agricultural use.

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