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Hydrogeochemical Characterisation, Heavy Metal Bioaccumulation in Fish and Aquatic Species, and Public Health Risk Assessment of River Benue, Nigeria

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ABSTRACT

This study assessed the hydrogeochemical characteristics, heavy metal bioaccumulation in fish and aquatic species, and associated public health risks in River Benue, Nigeria. Water samples and aquatic species including fish, shrimp, crab and molluscs were analysed for physicochemical parameters and ten heavy metals: Pb, Cd, Cr, Hg, As, Ni, Cu, Zn, Fe and Mn using standard analytical procedures and Atomic Absorption Spectrophotometry. The results revealed spatial variations in water quality, with downstream locations exhibiting elevated turbidity (8.63 ± 0.84 NTU), biological oxygen demand (4.74 ± 0.49 mg/L), and chemical oxygen demand (14.02 ± 1.53 mg/L). Heavy metal concentrations in downstream water samples exceeded World Health Organization limits for Pb (0.024 ± 0.003 mg/L), Cd (0.007 ± 0.001 mg/L), Cr (0.068 ± 0.007 mg/L), As (0.014 ± 0.002 mg/L), Ni (0.031 ± 0.004 mg/L), Fe (0.71 ± 0.09 mg/L), and Mn (0.18 ± 0.03 mg/L). Bioaccumulation analysis showed higher metal accumulation in molluscs and crabs, with Pb ranging from 0.39 ± 0.05 to 0.61 ± 0.08 mg/kg and Cr ranging from 0.44 ± 0.06 to 0.71 ± 0.09 mg/kg. Public health risk assessment indicated Hazard Quotient values for Pb ranging from 1.21 to 1.84 and Hazard Index values ranging from 1.98 to 3.12, exceeding the acceptable safety threshold. The study concludes that River Benue is under increasing hydrogeochemical and anthropogenic contamination with significant implications for aquatic ecosystem sustainability, food safety and public health.

Keywords: *River Benue, hydrogeochemistry, heavy metals, bioaccumulation, public health risk assessment.*

1.0 Introduction

Freshwater ecosystems play vital roles in sustaining domestic water supply, fisheries, irrigation, transportation, agriculture and biodiversity in many developing countries, including Nigeria. Rivers serve as important ecological and socioeconomic resources for surrounding communities; however, increasing anthropogenic pressure has significantly altered the hydrochemical quality of many aquatic systems. Rapid urbanisation, agricultural runoff, industrial discharge, domestic wastewater disposal, hydrocarbon contamination and poor environmental management have contributed to progressive deterioration of river ecosystems across Nigeria [3,15,17].

Hydrogeochemical assessment is essential for understanding the physicochemical processes, contaminant distribution and ecological status of aquatic environments. Physicochemical parameters such as pH, turbidity, dissolved oxygen, biological oxygen demand and chemical oxygen demand are important indicators of aquatic ecosystem health and pollution status. Previous hydrochemical studies conducted in Brass Island, Bayelsa State [13], Choba River, Rivers State [15], Imiringi River [24], and agricultural runoff-impacted streams in Uyo [26] revealed varying levels of environmental degradation associated with anthropogenic contamination.

Similar hydrochemical disturbances have also been reported in groundwater systems vulnerable to oil pollution in Yenagoa, Bayelsa State [22].

Heavy metal contamination of aquatic ecosystems remains one of the most significant environmental and public health concerns globally because heavy metals are persistent, toxic and capable of bioaccumulating within aquatic food chains. Metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg) and nickel (Ni) may accumulate in water, sediments and aquatic organisms at concentrations capable of causing ecological and toxicological effects. Studies conducted in the Nun River [1], Orashi River [7], Qua Iboe River sediments [23], Forcados River [27], Ogboinbiri Creek [25], and Andoni oil-bearing communities [47] demonstrated elevated heavy metal concentrations in aquatic systems associated with anthropogenic and hydrocarbon-related activities.

Fish and other aquatic organisms are widely recognised as effective bioindicators of aquatic pollution because of their ability to accumulate contaminants from water and sediments. Bioaccumulation of heavy metals in seafood and aquatic species has become an increasing concern due to its implications for food safety and public health. Previous studies on river-caught catfish in Rivers State [9], seafood from Kaa coastal market [2], blue crab from oil-polluted creeks in the Niger Delta [33], and Callinectes sapidus from Iko River [34] revealed significant accumulation of Pb, Cd, As and Hg in edible aquatic tissues. Similarly, heavy metal contamination has been reported in smoked-dried fish sold in Eke-Awka market [29] and estuarine fish exposed to petroleum hydrocarbons in the Qua Iboe Estuary [16].

Apart from ecological impacts, prolonged human exposure to contaminated aquatic resources may result in serious health complications including neurological disorders, kidney dysfunction, cardiovascular diseases, developmental abnormalities and carcinogenic effects. Public health risk assessments conducted in contaminated drinking water systems [4,10,12], seafood [2], estuarine fish [25], and hydrocarbon-impacted aquatic environments [16] have shown Hazard Quotient and Hazard Index values exceeding acceptable safety limits. These findings suggest increasing risks associated with long-term dietary exposure to contaminated aquatic organisms and polluted water sources.

River Benue is one of the largest freshwater systems in Nigeria and supports extensive fishing, irrigation, transportation and domestic activities for millions of people across the country. Despite its environmental and socioeconomic importance, comprehensive information regarding hydrogeochemical conditions, heavy metal contamination, aquatic bioaccumulation and associated public health risks within the river system remains limited. Most previous studies in Nigeria have focused on isolated investigations involving groundwater quality [13], sediment contamination [7,23], hydrocarbon pollution [25,27], or aquatic bioaccumulation studies in estuarine environments [16,33,34].Therefore, there is a need for an integrated assessment of River Benue to provide a comprehensive understanding of water quality deterioration, heavy metal distribution, contaminant bioaccumulation in fish and aquatic species, and associated public health implications.

2.0 Materials and Methods

2.1 Study Area

This study was conducted along selected sections of River Benue, Nigeria.

River Benue is one of the major inland freshwater systems in Nigeria and serves as an important source of domestic water supply, artisanal fisheries, irrigation, transportation, and socioeconomic activities for surrounding riverine communities. The river traverses several agricultural and urban settlements where increasing anthropogenic activities may influence water quality and aquatic ecosystem integrity.The study covered selected upstream, midstream, and downstream locations along River Benue to evaluate spatial variations in hydrogeochemical characteristics and heavy metal contamination within the aquatic environment. The study area lies within the tropical climatic zone characterised by distinct wet and dry seasons, with annual rainfall ranging between 1200 and 1800 mm and average temperatures ranging from 25 to 32 °C.

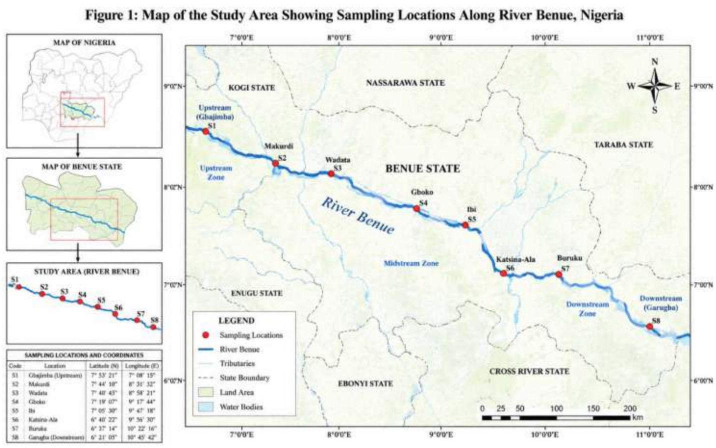

Figure 1: Map of the Study Area Showing Sampling Locations Along River Benue, Nigeria

2.2 Research Design

The study adopted a multidisciplinary environmental and public health research design involving hydrogeochemical assessment, heavy metal analysis, aquatic bioaccumulation evaluation, and public health risk assessment. The design enabled comprehensive evaluation of water quality, heavy metal distribution, contaminant bioaccumulation in aquatic organisms, and associated human health implications within the River Benue ecosystem.

2.3 Sample Collection and Sampling Technique

Water and aquatic species samples were collected from designated upstream, midstream, and downstream sections of River Benue using purposive sampling techniques based on accessibility, fishing intensity, human activities, and environmental characteristics.

A total of eighteen (18) water samples were collected using pre-cleaned polyethylene sampling bottles following standard environmental sampling procedures. Samples were collected approximately 20–30 cm below the water surface to minimise surface contamination. The collected samples were preserved in ice-packed containers and transported to the laboratory for analysis.

Aquatic species including catfish (*Clariasgariepinus*), tilapia (*Oreochromis niloticus*), freshwater shrimp, crab, and molluscs were obtained from local fishermen operating within the sampling locations. Representative samples of each species were collected and transported under refrigerated conditions for laboratory analysis.

2.4 Determination of Physicochemical Parameters

Physicochemical parameters including pH, temperature, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), and turbidity were determined using standard analytical procedures recommended by the American Public Health Association (APHA).

The pH and temperature values were measured in situ using a calibrated portable multiparameter meter. Dissolved oxygen was determined using the Winkler titration method, while biological oxygen demand was determined after five-day incubation at 20 °C. Chemical oxygen demand was determined using the dichromate reflux method, and turbidity was measured using a nephelometric turbidity meter.

2.5 Heavy Metal Analysis of Water Samples

Water samples were subjected to acid digestion using concentrated nitric acid prior to heavy metal analysis. The digested samples were filtered and analysed for ten heavy metals including lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), arsenic (As), nickel (Ni), copper (Cu), zinc (Zn), iron (Fe), and manganese (Mn).

Heavy metal concentrations were determined using Atomic Absorption Spectrophotometry (AAS). Calibration standards, reagent blanks, and duplicate analyses were employed to ensure analytical accuracy, precision, and quality assurance during laboratory procedures.

2.6 Heavy Metal Analysis of Fish and Aquatic Species

Edible tissues of fish and other aquatic species were carefully dissected, washed with distilled water, oven-dried at 105 °C, and homogenised prior to analysis. Approximately 1 g of each homogenised sample was digested using a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) under controlled laboratory conditions.

The digested samples were analysed for Pb, Cd, Cr, Hg, As, Ni, Cu, Zn, Fe, and Mn using Atomic Absorption Spectrophotometry. Concentrations obtained were compared with permissible limits established by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO).

2.7 Public Health Risk Assessment

Public health risk assessment associated with consumption of contaminated aquatic species was evaluated using Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI).

2.7.1 Estimated Daily Intake (EDI)

The Estimated Daily Intake was calculated using the equation:

$$EDI = (C \times IR \times EF \times ED) / (BW \times AT)$$

Where:

C = concentration of heavy metal in aquatic species (mg/kg)

IR = ingestion rate of fish/aquatic species (kg/day)

EF = exposure frequency (365 days/year)

ED = exposure duration (years)

BW = average body weight (kg)

AT = averaging time (days)

2.7.2 Hazard Quotient (HQ)

The Hazard Quotient for non-carcinogenic risk assessment was calculated using the equation:

$$HQ = EDI / RfD$$

Where:

EDI = Estimated Daily Intake

RfD = oral reference dose for the specific heavy metal (mg/kg/day)

Values of HQ greater than 1.0 indicate potential non-carcinogenic health risks.

2.7.3 Hazard Index (HI)

The cumulative non-carcinogenic risk associated with exposure to multiple heavy metals was calculated using the equation:

$$HI = \Sigma HQ$$

Where:

HI = Hazard Index

ΣHQ = sum of individual Hazard Quotient values for all analysed heavy metals

An HI value greater than 1.0 indicates potential adverse health effects associated with long-term exposure.

2.8 Bioaccumulation Factor (BAF)

The Bioaccumulation Factor was used to evaluate the transfer and accumulation of heavy metals from water into aquatic organisms. It was calculated using the equation:

$$BAF = Cb / Cw$$

Where:

Cb = concentration of heavy metal in aquatic organism tissue (mg/kg)

Cw = concentration of heavy metal in water (mg/L)

Higher BAF values indicate greater accumulation potential of metals within aquatic organisms.

2.9 Statistical Analysis

Descriptive statistical analyses including mean, standard deviation, frequency distribution, and percentage variations were used to analyse the generated data. Results were presented using tables and charts where appropriate.

Analysis of variance (ANOVA) was used to determine significant differences in physicochemical parameters and heavy metal concentrations among sampling locations and aquatic species. Statistical significance was considered at $p < 0.05$.All statistical analyses were performed using Statistical Package for Social Sciences (SPSS) version 25.0.

2.10 Quality Assurance and Quality Control

Quality assurance and quality control procedures were strictly maintained throughout sample collection, preparation, and laboratory analysis. Sampling bottles and laboratory glassware were thoroughly washed, acid-rinsed, and deionised prior to use.

Analytical accuracy was validated using reagent blanks, duplicate analyses, and calibration standards. Instrument calibration was performed before analysis, and all reagents used were of analytical grade.

2.11 Ethical Considerations

Ethical principles guiding environmental and public health research were strictly observed during the study. Necessary permissions were obtained from relevant local authorities and fishing communities prior to sample collection.

The study did not involve human clinical experimentation; however, all environmental sampling procedures complied with standard environmental safety and ethical research guidelines.

3.0 Results

3.1 Physicochemical Characteristics of River Benue Water Samples

The physicochemical characteristics of River Benue water samples collected from upstream, midstream, and downstream locations are presented in Table 3.1. The results revealed observable spatial variations in the hydrochemical properties of the river system across the sampling locations.

The pH values ranged from 6.28 ± 0.24 to 6.85 ± 0.18, indicating slightly acidic to near-neutral conditions. Upstream samples recorded comparatively higher pH values, whereas downstream locations exhibited lower pH levels, suggesting increasing anthropogenic influence along the river course. Water temperature ranged from 27.2 ± 1.1 °C to 29.6 ± 1.3 °C, with downstream locations exhibiting relatively elevated temperatures.

Dissolved oxygen (DO) concentrations decreased progressively from upstream (6.21 ± 0.42 mg/L) to downstream sections (4.11 ± 0.28 mg/L). The downstream values were below the recommended threshold for sustaining healthy aquatic ecosystems. In contrast, biological oxygen demand (BOD) and chemical oxygen demand (COD) values increased downstream, indicating elevated organic and chemical pollution within the river environment.

Turbidity values ranged between 3.62 ± 0.38 NTU and 8.63 ± 0.84 NTU. Midstream and downstream locations exceeded the World Health Organization (WHO) permissible limit of 5 NTU, suggesting increased suspended particulates, sediment load, and possible contamination from domestic, agricultural, and urban runoff sources.

Table 3.1: Physicochemical Parameters of River Benue Water Samples

Parameter	WHO Limit	Upstream Mean ± SD	Midstream Mean ± SD	Downstream Mean ± SD
pH	6.5–8.5	6.85 ± 0.18	6.51 ± 0.21	6.28 ± 0.24
Temperature (°C)	25–30	27.2 ± 1.1	28.4 ± 1.4	29.6 ± 1.3
Dissolved Oxygen (mg/L)	≥ 5.0	6.21 ± 0.42	4.92 ± 0.35	4.11 ± 0.28
Biological Oxygen Demand (mg/L)	≤ 3.0	2.11 ± 0.26	3.81 ± 0.41	4.74 ± 0.49
Chemical Oxygen Demand (mg/L)	≤ 10	8.26 ± 1.04	11.67 ± 1.28	14.02 ± 1.53
Turbidity (NTU)	≤ 5	3.62 ± 0.38	6.88 ± 0.71	8.63 ± 0.84

3.2 Heavy Metal Concentrations in River Benue Water Samples

The concentrations of heavy metals detected in River Benue water samples are presented in Table 3.2. The results demonstrated varying concentrations of the analysed metals across the sampling locations, with downstream sections generally exhibiting relatively higher concentrations than upstream locations.

Lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), nickel (Ni), iron (Fe), and manganese (Mn) exceeded WHO permissible limits in some midstream and downstream locations. Lead concentrations increased from 0.006 ± 0.001 mg/L upstream to 0.024 ± 0.003 mg/L downstream. Similarly, cadmium concentrations increased from 0.002 ± 0.001 mg/L upstream to 0.007 ± 0.001 mg/L downstream.

Chromium concentrations exceeded the WHO permissible limit of 0.05 mg/L in downstream samples, while arsenic concentrations ranged from 0.004 ± 0.001 mg/L upstream to 0.014 ± 0.002 mg/L downstream. Elevated iron and manganese concentrations were also observed downstream, indicating increasing mineral enrichment and anthropogenic contamination.

Mercury (Hg) was not detected in upstream samples but was detected at low concentrations in midstream and downstream locations. Copper (Cu) and zinc (Zn) concentrations remained below permissible limits across all sampling locations.

Table 3.2: Heavy Metal Concentrations in River Benue Water Samples

Heavy Metal	WHO Limit (mg/L)	Upstream	Midstream	Downstream
Lead (Pb)	0.01	0.006 ± 0.001	0.015 ± 0.002	0.024 ± 0.003
Cadmium (Cd)	0.003	0.002 ± 0.001	0.005 ± 0.001	0.007 ± 0.001
Chromium (Cr)	0.05	0.031 ± 0.004	0.049 ± 0.005	0.068 ± 0.007
Mercury (Hg)	0.001	ND	0.001 ± 0.000	0.002 ± 0.001
Arsenic (As)	0.01	0.004 ± 0.001	0.009 ± 0.001	0.014 ± 0.002
Nickel (Ni)	0.02	0.011 ± 0.002	0.023 ± 0.003	0.031 ± 0.004
Copper (Cu)	2.0	0.18 ± 0.03	0.24 ± 0.04	0.31 ± 0.05
Zinc (Zn)	3.0	0.62 ± 0.08	0.81 ± 0.11	1.04 ± 0.13
Iron (Fe)	0.30	0.28 ± 0.04	0.46 ± 0.06	0.71 ± 0.09
Manganese (Mn)	0.10	0.06 ± 0.01	0.12 ± 0.02	0.18 ± 0.03

ND = Not Detected

3.3 Heavy Metal Bioaccumulation in Fish and Aquatic Species

The concentrations of heavy metals accumulated in fish and other aquatic species including catfish (*Clariasgariepinus*), tilapia (*Oreochromis niloticus*), freshwater shrimp, crab, and molluscs are presented in Table 3.3. The results revealed significant variations in metal accumulation among the different aquatic species analysed.

Molluscs exhibited the highest concentrations of most heavy metals, followed by crab and fish species, while shrimp generally recorded comparatively lower concentrations. The observed accumulation trend suggests differential bioaccumulation capacities among aquatic organisms, particularly among benthic and bottom-feeding species.

Lead concentrations ranged from 0.39 ± 0.05 mg/kg in shrimp to 0.61 ± 0.08 mg/kg in molluscs, exceeding the FAO/WHO permissible limit of 0.30 mg/kg in most species analysed. Cadmium concentrations similarly exceeded recommended limits in crab and mollusc samples.

Chromium concentrations exceeded permissible limits in fish, crab, and molluscs, while arsenic concentrations were elevated in all analysed aquatic species. Nickel accumulation was particularly elevated in mollusc and crab samples, suggesting prolonged exposure to contaminated sediments and aquatic environments.

Mercury concentrations remained below the FAO/WHO permissible limit across all species analysed. Copper and zinc concentrations were comparatively higher but remained within acceptable safety limits.

Table 3.3: Heavy Metal Concentrations in Fish and Aquatic Species from River Benue (mg/kg)

Heavy Metal	FAO/WHO Limit	Fish Species	Shrimp	Crab	Molluscs
Lead (Pb)	0.30	0.48 ± 0.06	0.39 ± 0.05	0.52 ± 0.07	0.61 ± 0.08
Cadmium (Cd)	0.05	0.09 ± 0.02	0.07 ± 0.01	0.11 ± 0.02	0.13 ± 0.02
Chromium (Cr)	0.50	0.58 ± 0.07	0.44 ± 0.06	0.63 ± 0.08	0.71 ± 0.09
Mercury (Hg)	0.50	0.19 ± 0.03	0.14 ± 0.02	0.22 ± 0.03	0.24 ± 0.03
Arsenic (As)	0.10	0.13 ± 0.02	0.11 ± 0.02	0.16 ± 0.03	0.19 ± 0.03
Nickel (Ni)	0.20	0.24 ± 0.03	0.19 ± 0.03	0.27 ± 0.04	0.31 ± 0.05
Copper (Cu)	30.0	2.41 ± 0.31	2.12 ± 0.28	2.67 ± 0.34	2.88 ± 0.37
Zinc (Zn)	40.0	7.52 ± 0.84	6.31 ± 0.73	8.24 ± 0.92	9.11 ± 1.04
Iron (Fe)	20.0	10.41 ± 1.18	8.92 ± 1.03	11.64 ± 1.31	13.22 ± 1.44
Manganese (Mn)	1.0	0.88 ± 0.11	0.76 ± 0.09	1.12 ± 0.14	1.26 ± 0.16

3.4 Public Health Risk Assessment

The public health risk assessment indices for consumption of contaminated fish and aquatic species are presented in Table 3.4. The Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) values indicated increasing dietary exposure risks associated with regular consumption of aquatic resources from River Benue.

Estimated Daily Intake values exceeded the recommended threshold in crab and mollusc samples, indicating elevated exposure levels among consumers. Hazard Quotient values for lead, cadmium, and chromium exceeded the acceptable threshold value of 1.0 in several aquatic species, particularly molluscs and crab samples.

The cumulative Hazard Index values ranged from 1.98 in shrimp to 3.12 in molluscs, all exceeding the acceptable safety threshold of 1.0. These findings suggest potential non-carcinogenic health risks associated with long-term dietary exposure to contaminated aquatic resources from River Benue.

Table 3.4: Public Health Risk Assessment Indices for Consumption of Aquatic Species

Risk Parameter	Fish	Shrimp	Crab	Molluscs	Permissible Limit
Estimated Daily Intake (EDI)	1.12	0.96	1.28	1.46	< 1.0
Hazard Quotient (HQ-Pb)	1.43	1.21	1.57	1.84	< 1.0
Hazard Quotient (HQ-Cd)	1.27	1.04	1.46	1.62	< 1.0
Hazard Quotient (HQ-Cr)	1.18	0.92	1.31	1.48	< 1.0
Hazard Index (HI)	2.41	1.98	2.76	3.12	< 1.0

4.0 Discussion

The hydrogeochemical assessment of River Benue revealed progressive deterioration in water quality from upstream to downstream locations, indicating increasing anthropogenic influence within the river system. The slightly acidic to near-neutral pH values recorded in this study (6.28 ± 0.24 to 6.85 ± 0.18) are comparable with the hydrochemical conditions reported in groundwater systems within Brass Island, Bayelsa State, where pH values ranged within slightly acidic conditions due to organic enrichment and anthropogenic contamination [13]. Similar hydrochemical trends were also observed in streams impacted by agricultural runoff in Uyo, Akwa Ibom State [26] and in groundwater systems vulnerable to oil pollution in Yenagoa, Bayelsa State [22]. The slight downstream decline in pH may be associated with increasing organic decomposition, wastewater input and sediment interactions.

The elevated turbidity value observed downstream (8.63 ± 0.84 NTU) exceeded the WHO permissible limit of 5 NTU and suggests substantial suspended sediment and particulate influx into River Benue. Comparable elevated turbidity levels have been reported in Choba River, Rivers State, where domestic wastewater discharge significantly altered water quality and increased sediment loading [15]. Similarly, Imiringi River in the Niger Delta exhibited increased turbidity associated with anthropogenic runoff and fisheries disturbances [24]. Increased turbidity in aquatic systems may reduce light penetration, impair primary productivity and alter ecological stability.

The observed increase in biological oxygen demand (4.74 ± 0.49 mg/L) and chemical oxygen demand (14.02 ± 1.53 mg/L) downstream further indicates organic and chemical pollution within River Benue. These values are higher than those reported for agricultural runoff-impacted streams in Uyo [26], but comparable to observations in polluted urban rivers within the Niger Delta [17]. Elevated BOD and COD values are indicators of increasing oxygen depletion and ecological stress, which may adversely affect fish metabolism, reproduction and aquatic biodiversity.

Heavy metal analysis showed elevated concentrations of Pb, Cd, Cr, As, Ni, Fe and Mn in downstream water samples. Lead concentration increased from 0.006 ± 0.001 mg/L upstream to 0.024 ± 0.003 mg/L downstream, exceeding the WHO permissible limit of 0.01 mg/L. Similar elevated Pb concentrations were reported in Nun River, Bayelsa State [1], Choba River [15], Ogboinbiri Creek [25], and surface waters of oil-bearing communities in Andoni, Rivers State [47]. The similarities suggest that anthropogenic activities such as urban runoff, waste disposal, agricultural inputs and hydrocarbon-related contamination contribute significantly to Pb enrichment in Nigerian aquatic environments.

Cadmium concentrations ranged from 0.002 ± 0.001 to 0.007 ± 0.001 mg/L, with downstream values exceeding the WHO permissible limit of 0.003 mg/L. Comparable Cd contamination has been documented in groundwater systems around Epie Creek, Yenagoa [10], hydrochemical studies in Andoni-Isiokwan [35], and ecotoxicological investigations in Benin City rivers [17]. Cadmium contamination is environmentally significant because of its persistence, toxicity and tendency to bioaccumulate in aquatic organisms.

Chromium concentration reached 0.068 ± 0.007 mg/L downstream, exceeding the WHO permissible limit of 0.05 mg/L. Similar Cr enrichment patterns have been reported in Orashi River sediments [7], estuarine sediments of the Qua Iboe

River [23], and hydrocarbon-impacted environments in Forcados River [27]. Chromium contamination in aquatic environments may originate from industrial discharge, metal corrosion, geochemical weathering and urban waste inputs.

The elevated iron concentration (0.71 ± 0.09 mg/L) and manganese concentration (0.18 ± 0.03 mg/L) observed downstream exceeded WHO permissible limits and indicate strong hydrogeochemical and sediment-associated influence. Similar Fe and Mn enrichment patterns have been reported in groundwater vulnerability assessments in Yenagoa [22] and hydrochemical studies in Bayelsa State [13]. Elevated Fe and Mn concentrations may result from mineral dissolution, reducing conditions and anthropogenic enrichment within aquatic systems.

The bioaccumulation results revealed substantial transfer of heavy metals into fish and aquatic organisms. Molluscs accumulated the highest Pb concentration (0.61 ± 0.08 mg/kg), followed by crab (0.52 ± 0.07 mg/kg) and fish species (0.48 ± 0.06 mg/kg), all exceeding the FAO/WHO permissible limit of 0.30 mg/kg. Similar Pb accumulation patterns were reported in blue crab from oil-polluted creeks in the Niger Delta [33], Callinectes sapidus from Iko River [34], and river-caught catfish in Rivers State [9]. The elevated concentrations observed in benthic organisms may be linked to prolonged sediment interaction and bottom-feeding behaviour.

Cadmium concentrations in molluscs (0.13 ± 0.02 mg/kg) and crab (0.11 ± 0.02 mg/kg) exceeded the FAO/WHO permissible limit of 0.05 mg/kg. Comparable Cd bioaccumulation trends were observed in seafood from Kaa coastal market [2], smoked-dried fish sold in Eke-Awka market [29], and estuarine fish exposed to petroleum hydrocarbons in the Niger Delta [16]. Cadmium accumulation in aquatic organisms poses significant toxicological concerns because of its association with renal damage, skeletal disorders and carcinogenicity.

Chromium concentration in molluscs reached 0.71 ± 0.09 mg/kg, exceeding the permissible limit of 0.50 mg/kg. This value was higher than concentrations reported in smoked and dried fish consumed in Nigeria [28] and Nile tilapia processed under different conditions [40]. The elevated Cr accumulation indicates active contaminant transfer through the aquatic food chain and suggests continuous exposure of aquatic organisms to contaminated sediments and water.

Arsenic concentrations ranged from 0.11 ± 0.02 to 0.19 ± 0.03 mg/kg, exceeding permissible limits in most aquatic species analysed. Similar arsenic contamination patterns have been reported in BTEX- and PAH-contaminated environments in Bonny River [32], Ogboinbiri Creek [25], and hydrocarbon-polluted estuarine ecosystems [16]. Arsenic exposure through seafood consumption may increase risks of carcinogenicity, cardiovascular disorders and neurological complications.

The public health risk assessment revealed Hazard Quotient values for Pb ranging from 1.21 to 1.84 and cumulative Hazard Index values ranging from 1.98 to 3.12. These values exceeded the acceptable threshold value of 1.0, indicating potential non-carcinogenic health risks among consumers of aquatic resources from River Benue. Similar elevated Hazard Index values have been reported in Nun River [1], Diobu water systems [12], contaminated seafood from Rivers State [2], and estuarine fish from Andoni River [25]. The higher Hazard Index observed in molluscs (3.12) further confirms the importance of benthic organisms as major pathways for human exposure to heavy metals in aquatic ecosystems.

The ecological implications of these findings are substantial. Elevated heavy metal concentrations and deteriorating hydrochemical conditions may affect aquatic biodiversity, fish productivity and ecosystem sustainability. Similar ecological concerns have been reported in Orashi River [8], Bonny Estuary [18], Qua Iboe Estuary [16], and Andoni River [31], where contaminant accumulation affected aquatic organisms and ecosystem health. Continuous exposure of aquatic organisms to toxic metals may result in physiological stress, altered reproductive performance, histopathological damage and reduced ecological resilience.

5.0 Conclusion

This study assessed the hydrogeochemical characteristics, heavy metal bioaccumulation in fish and aquatic species, and associated public health risks in River Benue, Nigeria. The findings revealed significant spatial variations in physicochemical parameters and heavy metal concentrations across the river system, with downstream locations showing greater evidence of hydrochemical deterioration and contaminant enrichment. Elevated turbidity, biological oxygen demand and chemical oxygen demand values indicated increasing anthropogenic pressure on the aquatic environment.

The concentrations of Pb, Cd, Cr, As, Ni, Fe and Mn in some water samples exceeded recommended permissible limits, suggesting substantial contamination from anthropogenic and geochemical sources. The study further demonstrated considerable bioaccumulation of heavy metals in fish, shrimp, crab and molluscs, with benthic organisms such as molluscs and crabs recording the highest contaminant burdens. Several heavy metals detected in aquatic organisms exceeded FAO/WHO permissible limits for edible aquatic species, indicating significant food safety concerns.

Public health risk assessment showed Hazard Quotient and Hazard Index values above acceptable thresholds, particularly for Pb, Cd and Cr, suggesting potential non-carcinogenic health risks associated with long-term consumption of contaminated aquatic resources from River Benue. The findings therefore indicate that the river ecosystem is increasingly vulnerable to hydrogeochemical pollution, ecological degradation and toxicological risks.

The study concludes that River Benue is under significant environmental stress arising from anthropogenic contamination and hydrogeochemical processes, with implications for aquatic ecosystem sustainability, fisheries productivity, food safety and human health. Continuous environmental monitoring, enforcement of pollution control measures, proper waste management practices and routine assessment of aquatic food safety are strongly recommended to protect the river ecosystem and safeguard public health.

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