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Full paper

Assessment of Petroleum Hydrocarbons in Water Samples within Borno State, Nigeria

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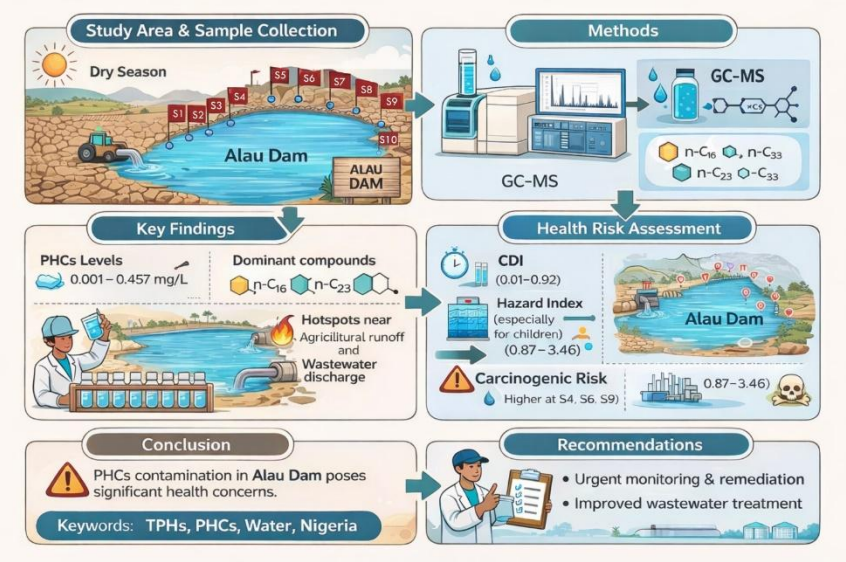
Abstract

Petroleum hydrocarbons (PHCs) are persistent pollutants with serious ecological and health implications, especially in oil-impacted aquatic systems. This study evaluated the concentration, distribution, and health risks of PHCs in dry-season water samples from Alau Dam, Konduga LGA, Borno State, Nigeria. Water from ten sampling points S1–S10 was analyzed using GC–MS. PHCs concentrations ranged from 0.001 to 0.457 mg/L, with elevated levels near agricultural runoff and wastewater discharge areas. Dominant compounds included n-alkanes such as n-C16, n-C23, and n-C33. CDI values ranged from 1.12×10^{-5} to 8.43×10^{-3} mg/kg/day. Hazard Quotients (0.01–0.92 suggested low individual risk; however, cumulative Hazard Index values exceeded safety limits at several sampling points, particularly for children 0.87–3.46. Carcinogenic risks were above USEPA limits, with higher risks at S4, S6, and S9. Overall, PHCs contamination poses significant health concerns, warranting urgent monitoring and remediation.



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1. Introduction

Petroleum hydrocarbons (PHCs) and total petroleum hydrocarbons (TPHs) are among the most widespread and persistent organic contaminants in aquatic systems, largely due to anthropogenic activities such as crude oil exploration, refining, transportation, industrial effluents, and urban runoff. Once discharged into aquatic ecosystems, PHCs undergo complex processes including dissolution, volatilization, photooxidation, biodegradation, and adsorption to sediments, but significant fractions remain in water bodies, thereby posing risks to ecological integrity and human health [3, 22]. These hydrocarbons are composed of diverse chemical structures, including alkanes, aromatics, and polycyclic aromatic hydrocarbons (PAHs), many of which are toxic, carcinogenic, or mutagenic [32].

In developing regions, particularly in oil-producing countries, the contamination of surface water and groundwater by petroleum hydrocarbons has emerged as a major environmental concern. Water resources in such areas are often directly linked to livelihood activities, including drinking, irrigation, aquaculture, and domestic uses, thereby increasing the risk of bioaccumulation and biomagnification in humans and wildlife [46].

In addition, chronic exposure to hydrocarbons through water has been associated with liver dysfunction, kidney impairment, immunotoxicity, endocrine disruption, and cancer [62]. Despite increasing global awareness of petroleum hydrocarbon pollution, many regions with significant oil-related activities still lack adequate monitoring frameworks and remediation strategies. Aquatic ecosystems in these areas remain under persistent threat of hydrocarbon contamination due to illegal refining, pipeline vandalism, oil spills, and industrial discharges [37]. This poses critical challenges for achieving Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation) and Goal 14 (Life Below Water). Furthermore, hydrocarbon-contaminated water not only undermines public health and food safety but also exacerbates socio-economic vulnerabilities, especially in rural and peri-urban communities that depend on local water sources for survival.

Another dimension of the problem is the inadequacy of up-to-date scientific data on hydrocarbon concentrations, exposure levels, and associated health risks in many impacted regions. While some studies have quantified TPHs in water, comprehensive evaluations that integrate exposure assessments, health risk indices, and comparisons with international guidelines remain limited [69]. This knowledge gap hampers effective policymaking, environmental management, and remediation planning.

The overarching aim of this study is to assess the levels, distribution, and potential health risks of total petroleum hydrocarbons in water resources within the selected study area, in order to provide evidence-based recommendations for environmental protection, risk mitigation, and sustainable water resource management.

2. Results and discussion

2.1 Levels of Total Petroleum Hydrocarbons (TPHs) in the Water Samples from Alau Dam, Konduga LGA, Borno State, Nigeria

Fig. 1 showed the mean concentrations of 35 Total Petroleum Hydrocarbons (TPHs) in water samples collected during the dry season at Alau Dam, Konduga, LGA, Borno State, Nigeria. Total Petroleum Hydrocarbons (TPHs) concentrations were detected in all sampling points (S1–S10). The highest Total Petroleum Hydrocarbons (TPHs) concentration was observed at S1 sampling point with the value of 9.29E-02 mg/L n-C8, while the lowest Total Petroleum Hydrocarbons (TPHs) concentration was observed at S2 sampling point with the value of 9.55E-06 mg/L pristine.

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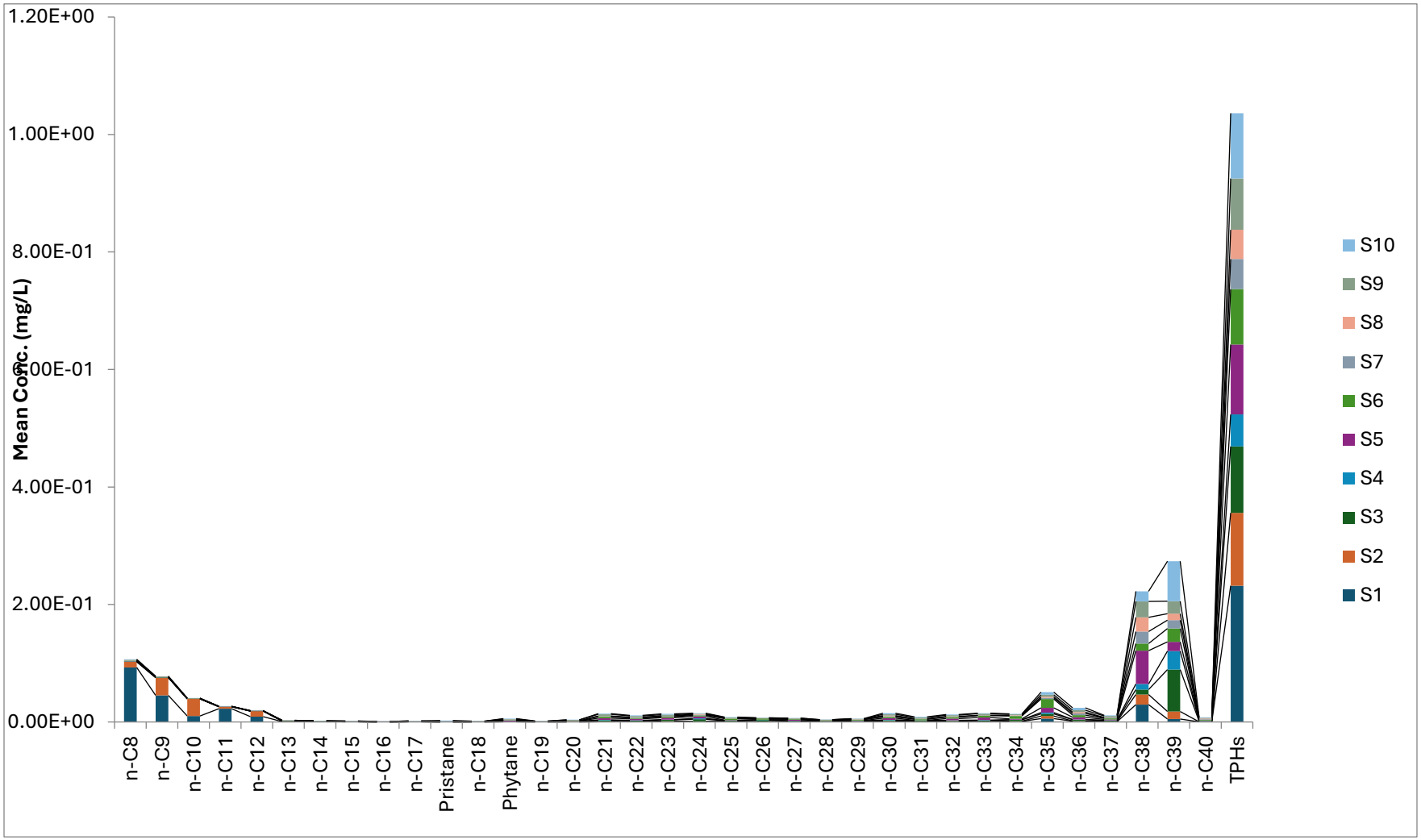

Fig 1. Mean Concentrations (mg/L) of Some Total Petroleum Hydrocarbons (TPHs) in Water Samples from Alau Dam, Konduga, Local Government Area, Borno State, Nigeria

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However Total Petroleum Hydrocarbons (TPHs) are released naturally into the environment due to accidental oil spillage, organic matter decomposition and anthropogenic activities such as petroleum exploration and the burning of fossil fuels [30, 12, 35]. The mean concentrations of Total Petroleum Hydrocarbons (TPHs) in water samples during the dry season which ranged from 9.55E-06 to 9.29E-02 mg/L were below EU standard limit of 300 mg/L. Total Petroleum Hydrocarbons (TPHs) has harmful effect on soil and water as well as human health, inhaling or swallowing large amount of some Total Petroleum Hydrocarbons (TPHs) e.g. gasoline can cause death [7]. Long term exposure to petroleum hydrocarbons **(**PHCs) to high levels of gasoline is associated with a range of disorders affect the central nervous system [7]. Petroleum Hydrocarbons **(**PHCs) released into the sea or Dam, normally during transportation leading to the pollution of several sites, and can eventually reach the coasts. Oil spills ranging from low level discharge to catastrophic accident threatened coastal environments [6]. A similar study of TPHs was carried out by [25] in water samples from ARAC Environment Aluu, River State, Nigeria. His finding value stood at 0.15 mg/L, such value was in line with that of the present study of 9.55E-06 to 9.29E-02 mg/L. Report by [24] on TPHs in water samples from Niger Delta, Nigeria, recorded the average value of 13.119 to 889 mg/L. Results from their finding were above the EU/WHO safety limits and also higher than value obtained from the present study. Similar studied were investigated by [22] on TPHs with the values of 0.053 to 61.596 mg/L. [29], recorded the average value range of 0.3 to 1.21 mg/L of TPHs in water sample which is below maximum permissible limit of 300 mg/L. [50], reported TPHs in water samples along estuary varied over a wide range of 2.0 – 19.1mg/L. According to FAO, Seawater containing hydrocarbons levels of less than 2.5 mg/L are considered as the natural back ground levels in a region. The TPHs concentrations in the Kundalike estuarine waters were considerably higher (Station 4 to Station 10) than the background level recorded from station 1 to 3 [50, 31] recorded the value of (5.22 µg/L) TPHs in Tigeris River, Iraq. [23] Levels of TPHs with average values (11.55-17.88 mg/L), in Northern part of Gulf of Suez, Egypt. In their findings, their results of TPHs obtained in water samples are higher than result of the present study with value of ranging from 9.55E-06 to 9.29E-02 mg/L [16], reported TPHs in atmospheric rainwater, River State, Nigeria with the average values of 9.1217 to 59.4923 mg/L both aliphatic and aromatic from April to October, 2019. The high concentrations of TPHs in the rainwater were relatively contaminated and unsafe for human consumption due to crude oil and gas processing releases into the atmosphere and subsequently as rainwater [16]. Their values obtained are not in agreement with that of the present study [11], carried out similar research on total petroleum and aliphatic hydrocarbons profile of the River Niger surface water at Okpu and Iyiowa-Odekpe regions in South-Eastern, Nigeria. The results of his study revealed a TPHs range of 1658-5436 mg/L with a mean of 2597 ±492 mg/L. The mean value for the rainy season 3284 ±1254 mg/L. The mean value for the rainy season 3283.783±1253.99µg/L was significantly higher than that of the dry season 1909.429±190.866 µg/L. Values for all the months at all sampled locations were also much higher than the European Union limit of 300 µg/L. However the results of his studied, contradict the values obtained in present studied, according to [11], the higher TPHs values obtained in his studied was due to rapid processing of crude oil in the studied area. Also research reported by[36], on distribution of total petroleum hydrocarbons in water and its impact on six commercially important fishes of Kundalika estuary, west coast of India Kundalika estuary, which opens into the Arabian Sea along the west coast of India, receives effluents from industries situated on its bank. The values of TPHs varied in water (2.0 to 19.1µg/L). Results of the above finding are higher than that of the present research (9.55E-06 to 9.29E-02 mg/L). However studied carried out by [60] and [26] on TPH in water samples ranged from 0.001 to 0.254 and 0.004 to 0.008 mg/L. In their findings, these values are below the [63] safety limits. Research carried out by [1], showed higher concentrations of some Petroleum hydrocarbon profiles of water samples of Algoa Bay in the Eastern Cape Province of South Africa, with TPHs values ranging from 45.07 to 307 µg/L, which showed high pollution level. Similar research was carried out by [9], on characteristic level of total petroleum hydrocarbon in groundwater of oil impacted area in the Niger Delta Region, Nigeria. Study shows that water samples obtained from all the stations were contaminated with TPH. At depth 0 to 0.5m the mean TPHs concentrations at Stations I, II, III, IV and V of water sample were (8186.67, 12110.00, 1351.67, 4137.00 and 9020.67 µg/L). These studies were in line with a similar study carried out by [5], on Petroleum hydrocarbon status of the Buffalo River Estuary in East London with results of TPHs ranging varied from 7.65 to 477 µg/L with mean values of 146.50 ± 27.96 µg/L. The results showed that TPH were slightly lower in summer than in autumn in the two environmental matrices. Their average amount of TPHs in the water samples collected from all the sampling stations was higher than the EU limit of 300 mg/L. The research carried out by [21], with value of 211,025.73 µg/L, such values were higher than that of present study [21], concluded that the higher TPHs in water samples could be as results of human activities and oil exploration

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in the studied area. Generally the mean concentrations of PHCs in water samples from Alau Dam, Konduga LGA, Borno State, were below the finding of [21], and also below maximum permissible limits [55, 63].

Extreme differences in TPH concentrations across regions and seasons are primarily driven by variations in anthropogenic activities, climatic conditions, and environmental characteristics. Areas with intensive oil exploration, industrial discharge, urbanization, agricultural activities, and transportation networks tend to exhibit elevated TPH levels. Seasonal factors such as rainfall, runoff, dilution, evaporation, and flooding strongly influence hydrocarbon distribution and concentration. Geographical and hydrological conditions, including proximity to pollution sources, water flow regimes, sediment to water interactions, and catchment characteristics, further contribute to spatial variability. Additionally, natural inputs from geological seepage, organic matter decomposition, biomass burning, and microbial processes affect background TPH levels at both local and global scales

Short-chain hydrocarbons may dominate water samples despite their volatility because they are continuously replenished by recent petroleum inputs and have higher aqueous solubility than long-chain compounds. In contrast, long-chain hydrocarbons are strongly hydrophobic and preferentially partition into sediments, leading to lower concentrations in the water column. Faster biodegradation of heavier fractions in sediments and possible analytical bias favoring lighter compounds can further enhance this pattern. Therefore, their dominance reflects source characteristics and environmental partitioning rather than volatility alone. S1 and S2 are closer to active or recent contamination sources than the other sampling locations. Their distinct behavior like higher concentrations likely reflects localized inputs such as urban runoff, fuel handling areas, irrigation return flows, boat activity and point-source discharges. Therefore, S1 and S2 are special not because of intrinsic properties of the samples, but because their locations are more directly influenced by petroleum inputs and conditions that favor retention of hydrocarbons compared with the other sites.

Even when TPH concentrations are below international limits, cumulative risk can arise due to their persistence, chronic exposure, and bioaccumulative potential. Repeated low-level exposure through drinking water, dermal contact, and consumption of contaminated aquatic organisms may pose long-term health and ecological risks. Sensitive species, early life stages, and vulnerable human populations may be affected at concentrations considered safe by regulatory standards. Therefore, cumulative risk assessment should integrate exposure duration, multiple pathways, ecological sensitivity, and bioaccumulation rather than relying solely on guideline threshold values

2.2. Chronic Daily Intake (mg/kg/day) of Some Total Petroleum Hydrocarbons (TPHs) in Water Samples via Ingestion and Dermal Contact from Alau Dam, Konduga Local Government Area, Borno State, Nigeria

Recent studies indicate that chronic exposure to petroleum hydrocarbons in drinking water could lead to long-term health risks, including liver toxicity, kidney damage, and potential carcinogenic effects [59]. TPHs in water typically occur after oil spills, leaks, or improper disposal of petroleum products. Chronic exposure to even low levels of these substances over time can lead to adverse health outcomes, particularly in vulnerable populations such as children and the elderly [51].

Fig. 2 and Fig. 3 show the CDI values for PHCs in water samples from study area (S1 to S10). This aligns with risk assessment principles for both children and adults however children have lower body weight, higher water intake per unit weight, and more vulnerable physiology [61]. The ingestion, showed CDIs ranging from 1.89E-05 mg/kg/day (n-C8, S4) to 4.74E-03 mg/kg/day (n-C39, S3). For dermal exposure, CDIs reached 3.80E-03 mg/kg/day (n-C37, S5) and 4.55E-03 mg/kg/day (n-C39, S10).

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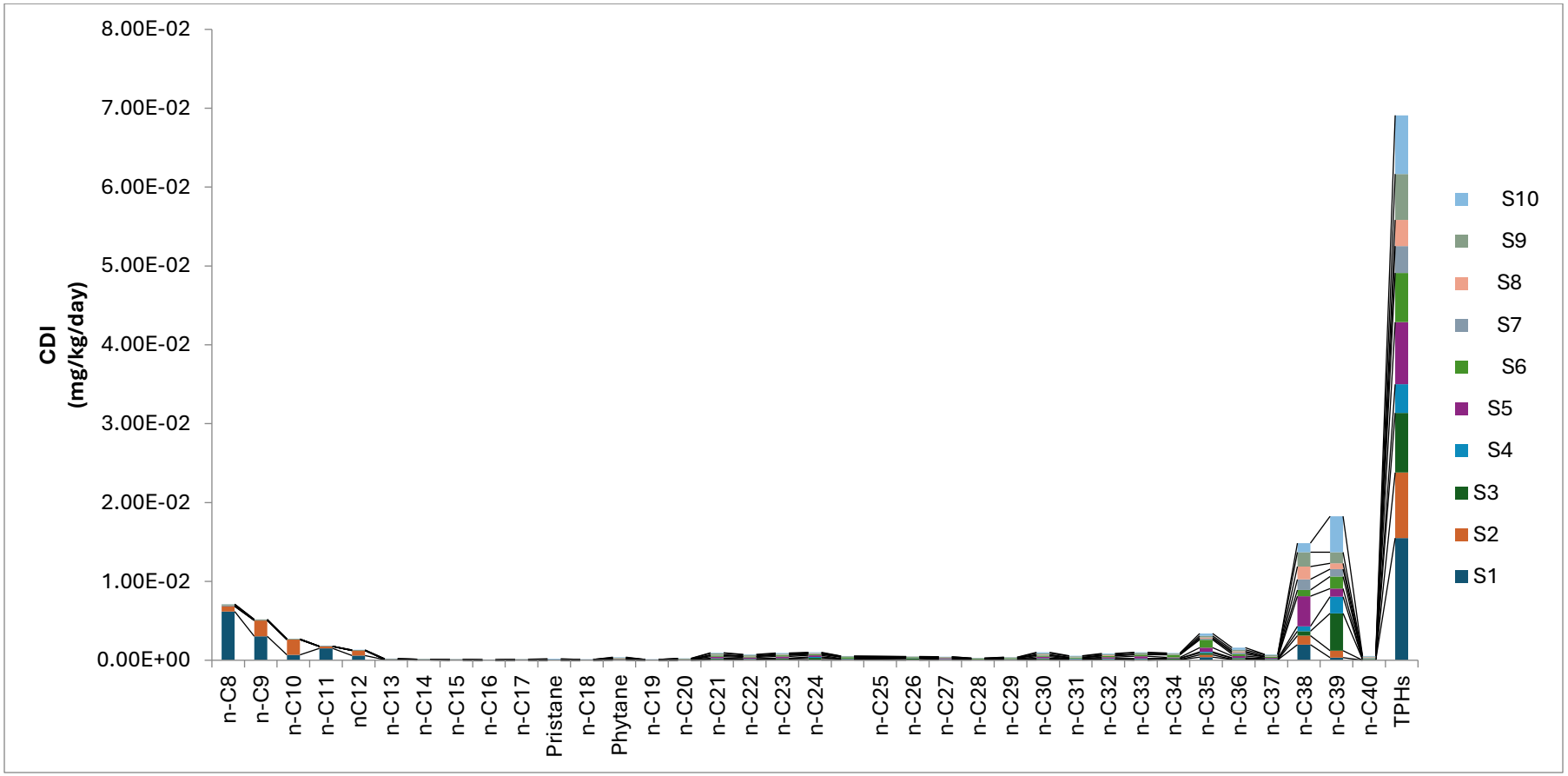

Fig 2. Chronic Daily Intake (mg/kg/day) of Some Total Petroleum Hydrocarbons (TPHs) in Water Samples via Ingestion from Alau Dam, Konduga Local Government Area, Borno State, Nigeria

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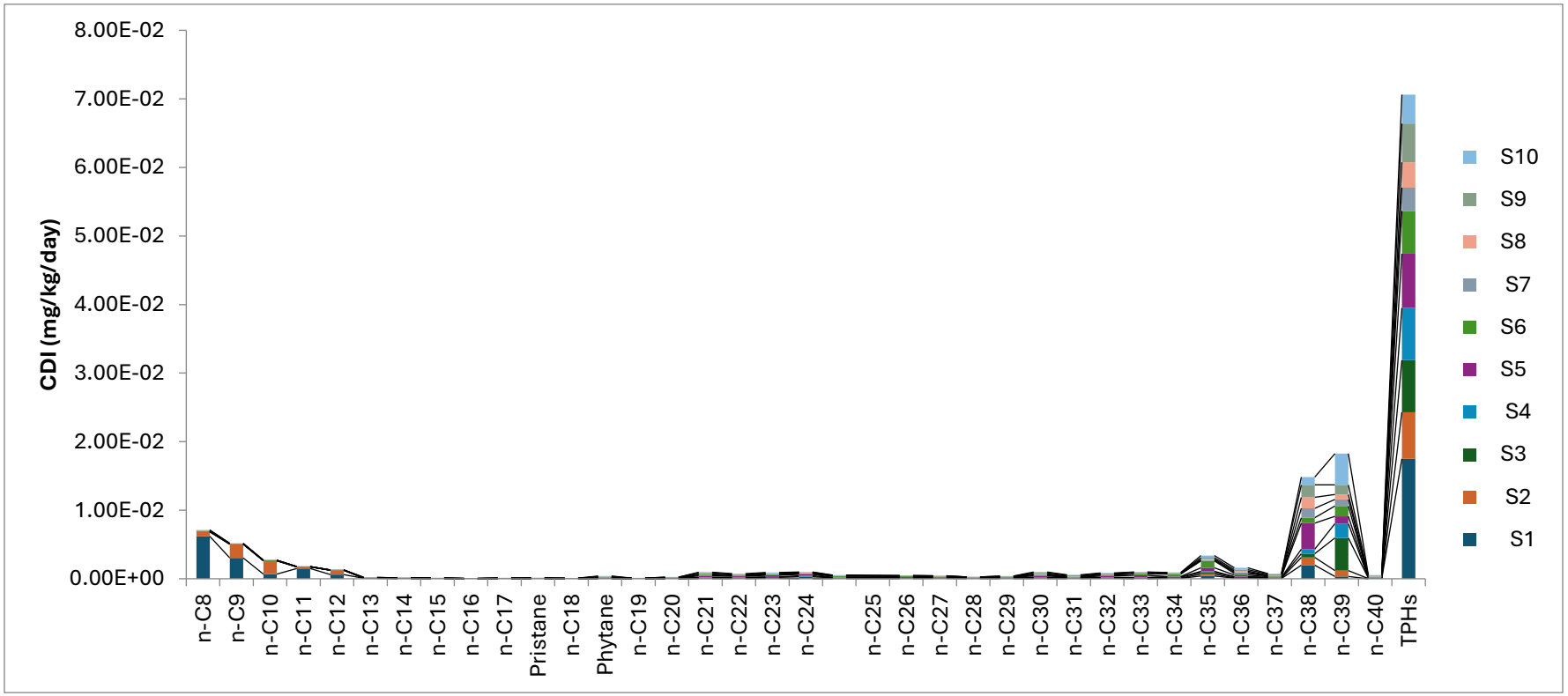

Fig 3. Chronic Daily Intake (mg/kg/day) of Some Total Petroleum Hydrocarbons (TPHs) in Water Samples via Dermal Contact from Alau Dam, Konduga Local Government Area, Borno State, Nigeria

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The findings of this research work are in consistent with findings in hydrocarbon-contaminated waters [33, 15]. The light fractions (n-C8–n-C16) recorded low CDI values (10^{-6}–10^{-3} mg/kg/day).

These fractions are volatile, soluble, and often linked to acute toxicity like neurological impairment [59]. The low to moderate CDI observed may reflect both their volatility and partial biodegradation in aquatic systems [44]. Similar ranges were reported in polluted rivers in Ghana and Niger Delta [29], confirming that short-chain hydrocarbons dominate initial ingestion exposure risks. Mid-Chain Hydrocarbons (n-C17 to n-C24, plus Pristane & Phytane) Pristane and phytane showed moderate to high CDIs: phytane up to 8.60E-05 mg/kg/day (ingestion) and 6.23E-05 mg/kg/day (dermal). These biomarkers of crude oil are relatively resistant to biodegradation, hence their persistence in water [10], n-C20 to n-C24 exhibited higher CDIs compared to short-chain PHCs, e.g., n-C21 ingestion up to 1.94E-04 mg/kg/day and dermal up to 1.97E-04 mg/kg/day. Such mid-chain hydrocarbons are less volatile and more stable, explaining their higher presence in water bodies [52]. These findings are consistent with studies in Malaysia and Nigeria where n-C17–n-C24 dominated petroleum hydrocarbon risks in water [20].

Long-Chain Hydrocarbons (n-C25 to n-C40) Long-chain fractions showed the highest CDI values, particularly n-C35, n-C37, n-C38, and n-C39. For ingestion in children: n-C35 peaked at 1.01E-03 mg/kg/day (S6). n-C38 reached 3.80E-03 mg/kg/day (S5). n-C39 recorded the highest ingestion CDI 4.74E-03 mg/kg/day (S3). For dermal exposure:n-C38 was consistently high, with 1.97E-03 to 3.80E-03 mg/kg/day across sites. n-C39 peaked at 4.55E-03 mg/kg/day (S10). Long-chain hydrocarbons are hydrophobic, tend to adsorb to sediments, and bioaccumulate in tissues, raising chronic exposure concerns [47]. Comparable high long-chain n-alkane exposure was documented in Egyptian irrigation canals and Chinese reservoirs [65, 68].

Highest CDIs values were often at S1, S5, S6, S9, and S10, suggesting local contamination sources likely petroleum runoff or anthropogenic inputs. For instance, S3 showed the highest n-C39 ingestion CDI (4.74E-03), while S5 recorded maximum n-C38 (3.80E-03). Similar site-specific variability was reported in oil-impacted Niger Delta Rivers, attributed to illegal refining and surface runoff [40]. The [59] and [64], WHO state that long-term PHC ingestion poses risks of hepatic, renal, neurological, and carcinogenic effects. CDI observed ranged from (10^{-3}–10^{-2} mg/kg/day) exceed typical reference doses for several hydrocarbon fractions (0.003–0.01 mg/kg/day), indicating potential non-cancer health risks. Chronic dermal exposure, especially to n-C35–n-C39, is concerning for both adults and children, as these hydrocarbons may enhance carcinogenic PAH bioavailability [48].

Similar hydrocarbon CDI patterns (children > adults, long-chain > short-chain, ingestion ≈ dermal) were observed in: Niger Delta, Nigeria [15]. Yangtze River, China [65]. Cairo irrigation canals, Egypt [67]. The persistence of n-C35–n-C39 fractions aligns with earlier global findings that higher molecular weight hydrocarbons resist natural degradation and dominate risk profiles [20].

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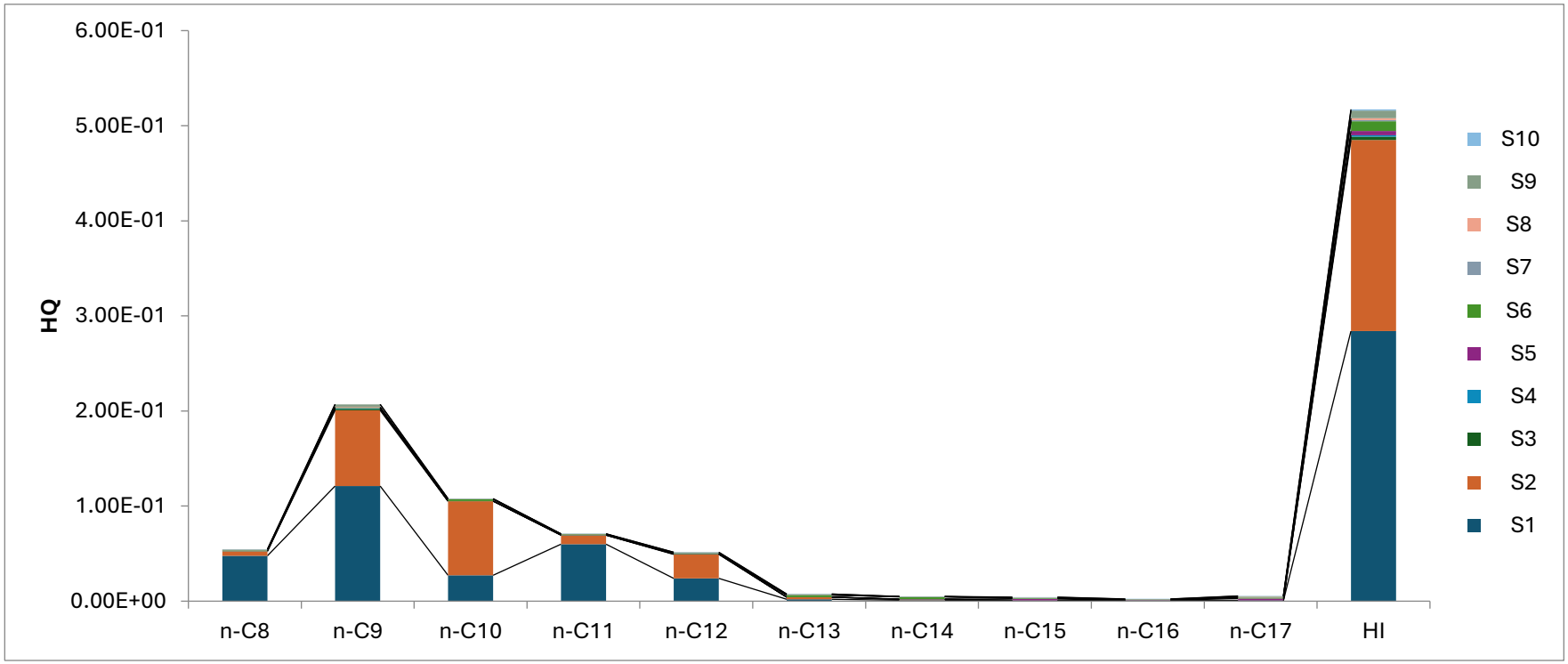

Fig 4. Hazard Quotient and Hazard Index of Total Petroleum Hydrocarbons (TPHs) for Non-Carcinogenic in Water via Ingestion from Alau Dam, Konduga LGA, Borno State, Nigeria

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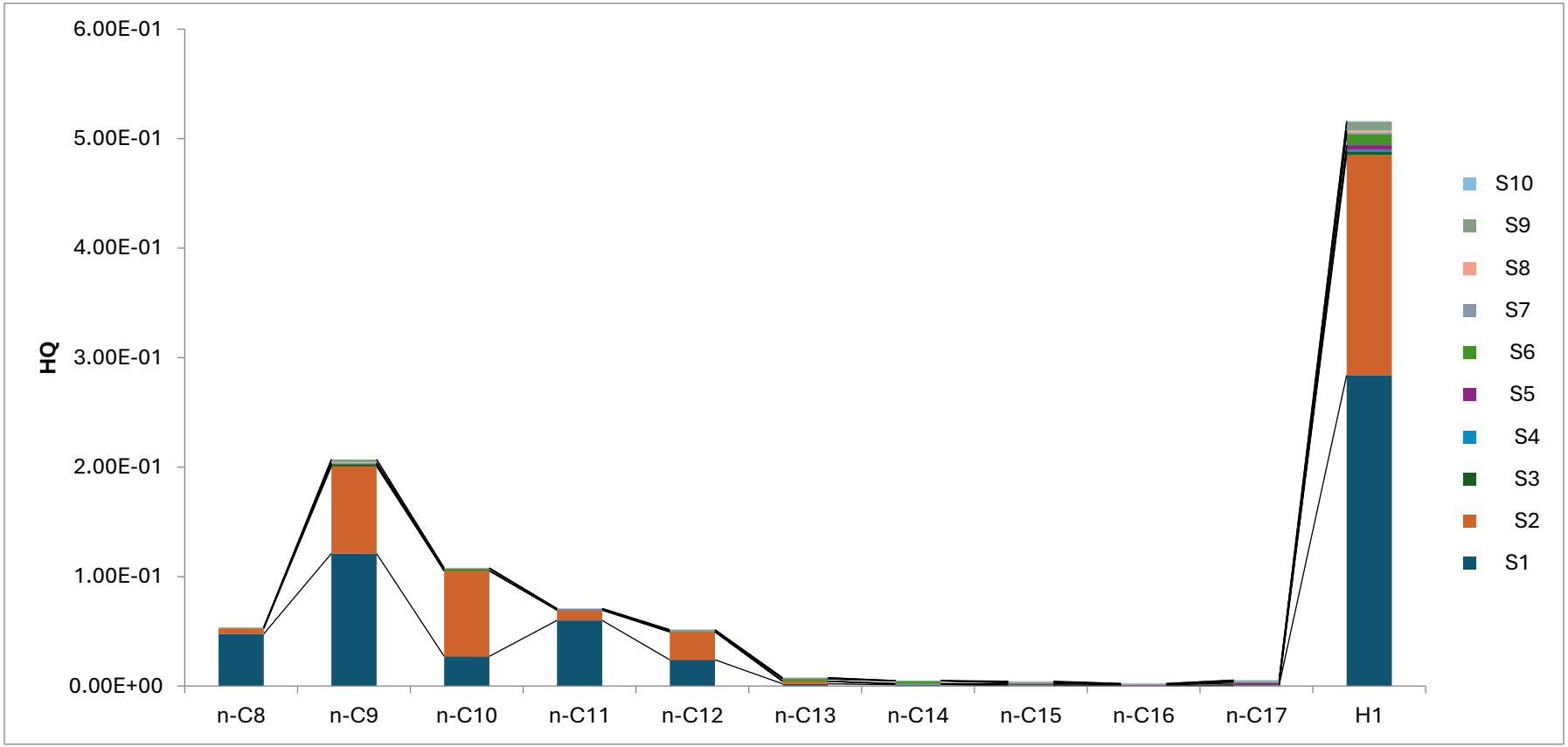

Fig. 5. Hazard Quotient and Hazard Index of Total Petroleum Hydrocarbons (TPHs) for Non-Carcinogenic in Water via Dermal Contact from Alau Dam, Konduga LGA, Borno State, Nigeria

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2.3. Hazard Quotient and Hazard Index of TPHs in Water Samples via Ingestion and Dermal Contact in Alau Dam, Konduga LGA, Borno State, Nigeria

Fig. 4 and Fig. 5 show the Hazard Quotient (HQ) the ratio of the chronic daily intake (CDI) of a contaminant to its reference dose (RfD). HQ < 1 unlikely to cause non-carcinogenic health effects. HQ ≥ 1 possible risk of adverse effects [58]. Hazard Index (HI). The cumulative sum of HQs from multiple PHCs. HI < 1 no significant health risk. HI ≥ 1 potential concern for human health. HI values ranged from 6.47E-04 (S4) to 1.22E-01 (S1). All sites recorded HI < 1, suggesting no significant non-carcinogenic risk. The highest HI (1.22E-01 at S1) was mainly influenced by contributions from n-C9 (5.21E-02) and n-C11 (2.58E-02), showing that light-chain hydrocarbons dominate exposure risk. Lowest HI values (S3–S4) indicate very minimal exposure, probably linked to lower PHC load in these sampling points. Similar findings were reported by [28], in groundwater near oil-spill sites in India, where adult HI values for hydrocarbons were below 1, indicating limited non-carcinogenic risks. Likewise, [40], in the Niger Delta found adult HI < 0.5, reflecting lower susceptibility in adults due to body weight and reduced ingestion rate compared to children [45], Even moderate HQ values for children are of concern because their metabolic systems are less developed, and exposure relative to body weight is higher. Studies globally confirm higher susceptibility of children [54], in Port Harcourt, Nigeria, found that children had HI values 3–5 times higher than adults in hydrocarbon-contaminated water [14], in China also reported that children consistently showed higher HI values, although still below 1 for aliphatic hydrocarbons. [64] emphasizes that children's ingestion rates and vulnerability increase non-carcinogenic risks, even when HI < 1. Although all HI < 1, long-term chronic exposure may still pose health concerns, especially if PHC input continues. Precautionary management is recommended because even sub-threshold HI values could lead to bioaccumulation in aquatic food webs [41]. Periodic monitoring and treatment strategies (e.g., activated carbon filtration) should be applied to prevent future escalation. Alau Dam water shows detectable petroleum hydrocarbons, but current exposure levels do not exceed safety thresholds. However, sustained pollution could push risks upward, especially for children and adult.

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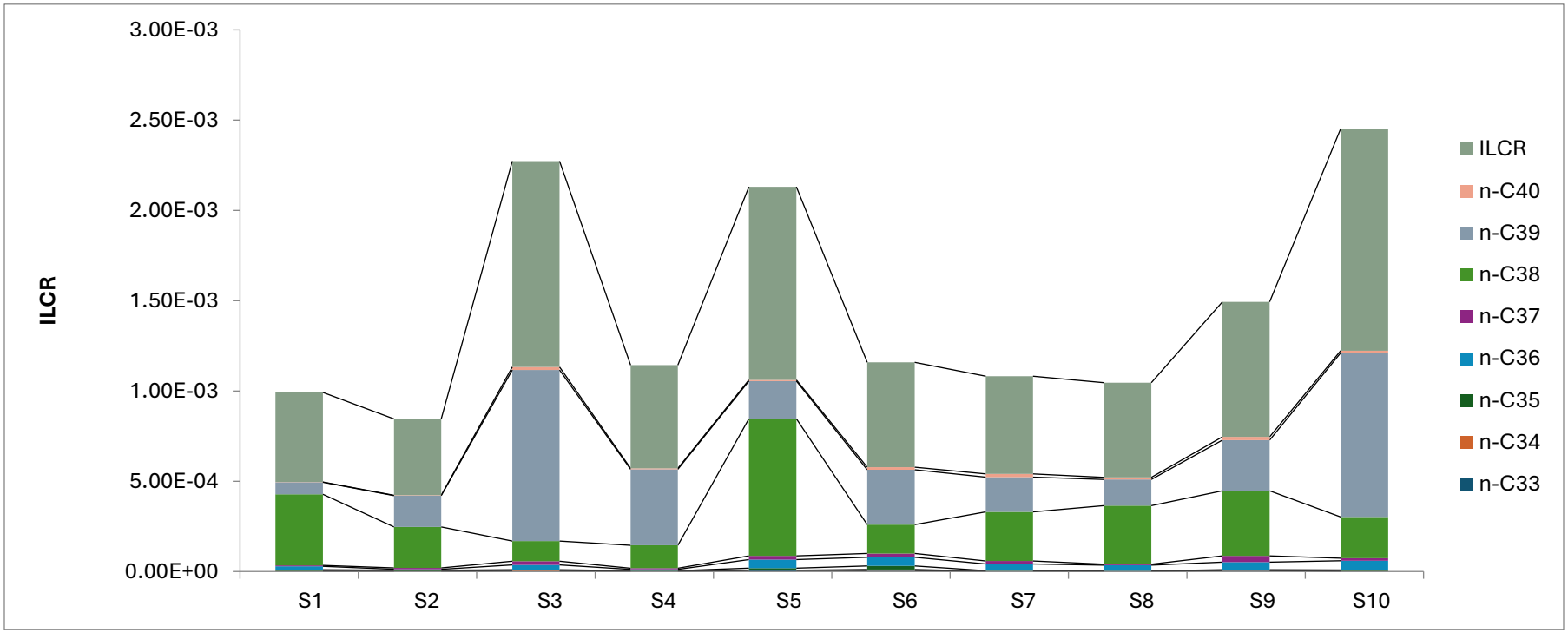

Fig. 6. Cancer Risk Assessment of Some Total Petroleum Hydrocarbons (TPHs) in Water Sample via Ingestion from Alau Dam, Konduga LGA, Borno State, Nigeria

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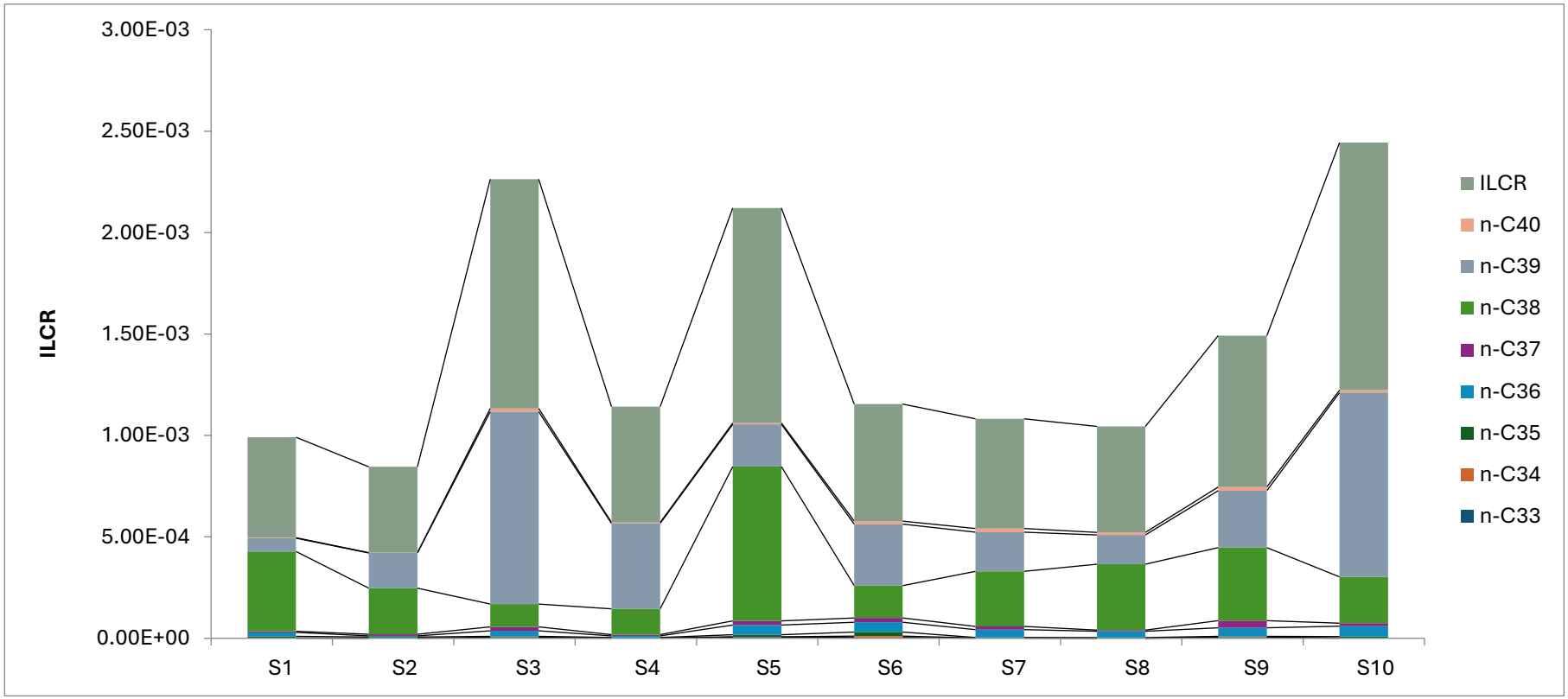

Fig. 7. Cancer Risk Assessment of Some Total Petroleum Hydrocarbons (TPHs) in Water Sample via Dermal Contact from Alau Dam, Konduga LGA, Borno State, Nigeria

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2.4. The Cancer Risk Values for Ingestion and Dermal Contact Pathways Reported as Incremental Lifetime Cancer Risk (ILCR) =

Fig. 6 and Fig. 7 show the ILCR Ranges Ingestion 4.23E-04 (S2) – 1.23E-03 (S10). Dermal contact: 4.23E-04 (S2) – 1.22E-03 (S10). These values are similar across both pathways, with ingestion showing slightly higher risks at some sites. According to the [57], acceptable cancer risk is between 1E-06 and 1E-04. Risks >1E-04 are considered unacceptable and of public health concern. In this study, all ILCR values exceeded 1E-04, with many falling within the 10^{-3} range, which implies a high probability of cancer risk from chronic PHC exposure, especially in children who are more vulnerable. n-C38 and n-C39 hydrocarbons recorded the highest individual contributions to ILCR (ranging from 1.12E-04 to 9.48E-04). These long-chain hydrocarbons are persistent, hydrophobic, and tend to bioaccumulate, increasing their carcinogenic potential in aquatic ecosystems [18]. In contrast, lower-chain hydrocarbons (e.g., n-C33, n-C34) had much smaller contributions (10^{-7}–10^{-6}), showing their lower relative impact on cancer risk.

Reported [[38] ILCR values in drinking water around Niger Delta communities ranging from 3.6E-05 to 2.5E-04, mostly within or slightly above the USEPA acceptable range. Compared to Alau Dam, the risks here are much higher, especially from n-C38 and n-C39. [42], found ILCR values from PHCs in groundwater near oil spill sites in Lagos ranging between 1.2E-04 and 6.5E-04, which is comparable but slightly lower than the current study's maximum values.

Assessed PHCs in drinking water in Pakistan [27] and found ILCR between 8.5E-06 and 4.2E-05, far below the levels in Alau Dam, showing that Nigerian inland waters near oil activity may have more severe contamination [4, 41, 18].

Guidelines stress that chronic exposure to PHCs beyond 1E-04 ILCR [57, 64] is a serious health risk, especially for children, who are more susceptible to genotoxic and mutagenic effects. The values in this study (up to 1.23E-03) exceed these thresholds, suggesting 1 in 1,000 children exposed may develop cancer over a lifetime, which is significantly higher than the global acceptable risk. Both ingestion and dermal pathways present unacceptable cancer risks to children, but ingestion appears slightly more critical. The elevated risks indicate that Alau Dam water is unsafe for direct consumption and domestic use without treatment. The dominance of high molecular weight hydrocarbons (n-C38, n-C39) suggests sources from petroleum leakage, runoff from oil-related activities, and incomplete combustion products, consistent with anthropogenic pollution patterns in Nigerian inland waters [19, 2]. The cancer risk assessment shows that children and adult are exposed to PHCs in Alau Dam face significant carcinogenic risks, with ILCR values well above the USEPA and WHO safety thresholds. Compared with studies across Nigeria and Asia, the risks from Alau Dam are on the higher end, indicating a critical environmental and public health concern. Urgent intervention is needed, including water treatment, pollution control, and continuous monitoring, to safeguard vulnerable populations [66].

The substantially higher ILCR values observed at Alau Dam compared with the Niger Delta, Lagos, and international sites such as Pakistan can be attributed to several interrelated factors. Alau Dam is a semi-enclosed reservoir with low water exchange, which promotes the retention and accumulation of hydrocarbons, unlike coastal or riverine systems that benefit from tidal flushing and dilution. Intense localized anthropogenic activities including agricultural runoff, improper waste disposal, fuel leakage from irrigation pumps, fishing boats, and artisanal mechanical operations introduce persistent petroleum contaminants directly into the dam. In addition, the hydrocarbon profile at Alau Dam is dominated by high molecular weight, long-chain hydrocarbons that are hydrophobic, resistant to degradation, and prone to sediment accumulation, thereby increasing long-term exposure. Seasonal hydrological variations further concentrate pollutants during dry periods. Differences in sampling approaches, exposure assumptions, and inclusion of dermal pathways may also elevate ILCR estimates, but the magnitude of risk strongly indicates genuine environmental contamination.

Exceptionally high ILCR values arise from the combined effects of intense local anthropogenic pollution, hydrocarbon composition, hydrological conditions, and assessment methods. Continuous inputs from agriculture, fuel handling, waste disposal, and small-scale activities introduce persistent, high-molecular-weight hydrocarbons that accumulate in sediments and biota, increasing carcinogenic risk. Low flow, long residence times, and seasonal dynamics further limit dilution and degradation. Although conservative exposure assumptions may elevate estimates, the magnitude indicates genuine contamination, requiring prioritized regulatory intervention, pollution control, remediation, monitoring, and protection of vulnerable populations.

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Exceptionally high ILCR values at Alau Dam result from intense localized anthropogenic inputs, dominance of persistent long-chain hydrocarbons (n-C33–n-C39), and hydrological confinement that limits dilution and flushing. Agricultural runoff, waste disposal, fuel leakage, and seasonal concentration effects promote contaminant accumulation in sediments. Methodological inclusion of dermal exposure and child-specific assumptions further elevates risk estimates. High molecular weight hydrocarbons drive chronic cancer risk due to persistence and bioaccumulation, necessitating sediment-focused remediation, source control, restricted water use, and child-centered public health interventions.

3. Materials and Methods

3.1. Study Area

Alau Dam is one of the numerous small and medium size blessed dam in the North Eastern part of Nigeria. It was constructed in 1987 on the river Nggada for the purpose of supplying portable drinking water to Maiduguri Metropolis, with over 8000 hectares of farm land in the catchment area of the dam [13]. It lies on the latitude $11^0$41N and longitude $13^0$16E on the south east (SE) part of Maiduguri town at a distance of 16 KM away from the Borno State Capital. The dam has surface area of 56,000.00 hectare and total storage capacity of 9.50 million cubic meters active, active storage capacity of 1.12 108 m^3. The height of the dam is about 540 meters with crest length and crest elevation of 31.0 meters and 331.50 meters respectively [13]. The Alau Dam level rises during rainy season (June to September). Alau Dam is also used for commercial fishing activities. Socio economic activities within the dam include small and large scale agriculture, grazing, fishing and other activities which directly are dependent on the dam (Fig. 8). The Alau Dam is the main source of fish and vegetables to the Maiduguri metropolis and neighboring States. The domestic water supply within Maiduguri metropolis also come from this dam, Alau Dam received a wide variety of waste from agricultural land and from activities of insurgency within the Sambisa forest, industrial effluents, farming activities, waste water discharge from residential sources, pollution from vehicle exhaust and sewages contain organic and inorganic contaminants. These are directly dumped into the waterways by humans or during run – off by rainfall, also the solid waste discharged as a result of insurgency activities within the Sambisa Forest flow directly into dam. This waste generated might contaminate Alau Dam with a variety of PHCs acting as point sources. However, domestic usage and agricultural activities are carried out in the dam without due regard to the chemistry of the water [8].

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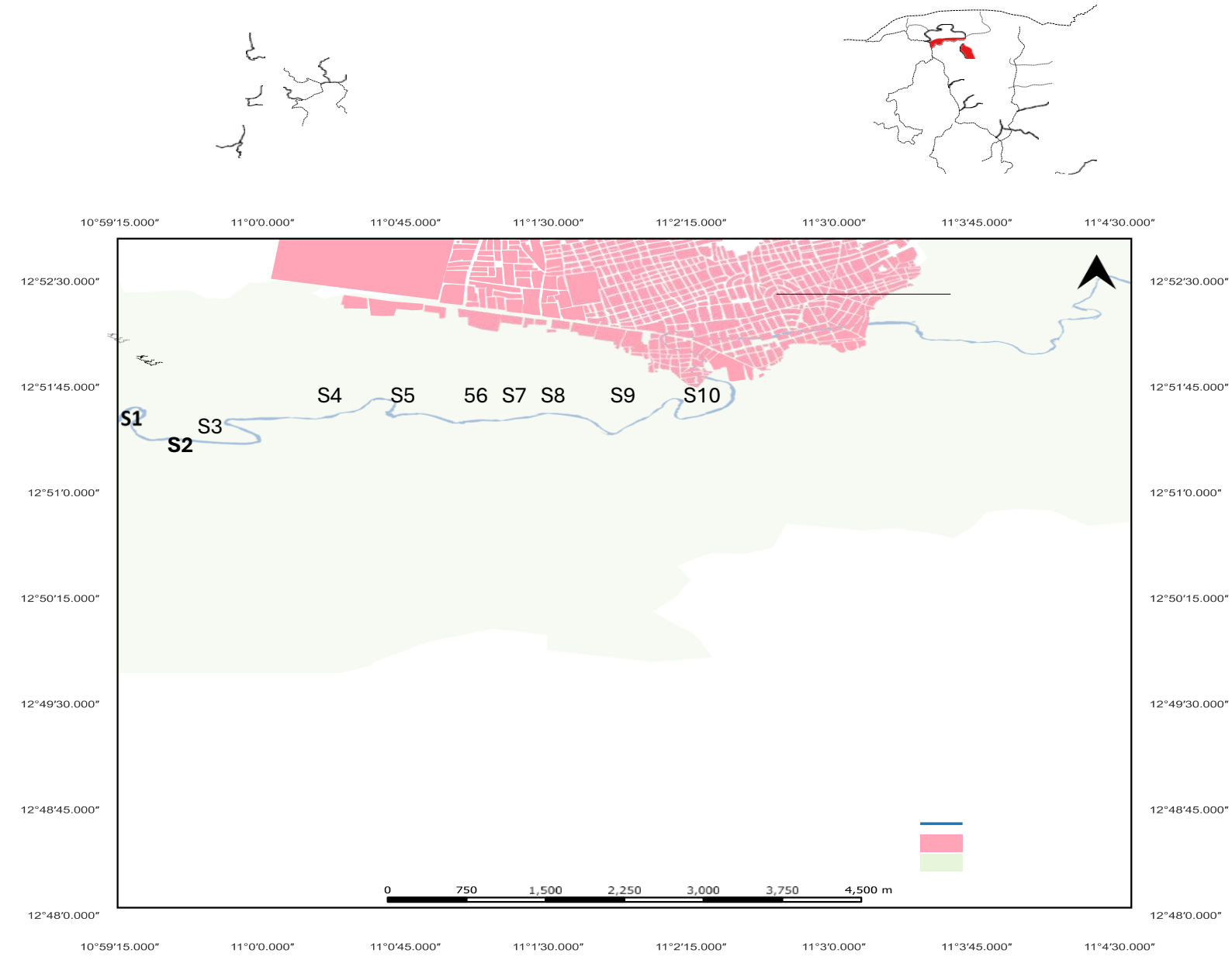

Fig 8. Show Sampling Locations (S1 to S10). Source: [1]

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3.2. Sample Collection

3.3. Water Sample Collection

Water samples were collected on (1th March to 30th May, 2025) in accordance with the method described by [8]. Water samples were collected within the Alau Dam, Konduga Local Government Area, Borno State, Nigeria from designated points S1 to S10 as indicated in the Fig 8. The sampling design consisted of triplicate water samples collected at each site during the study period. With ten (10) sampling points and three (3) replicate samples per site, a total of thirty (30) water samples were obtained and analyzed. Strict quality control measures were applied to prevent cross-contamination during sampling and transport. Pre-cleaned glass bottles were used, rinsed with site water before collection, and samples were taken upstream to avoid disturbance. Sampling equipment and gloves were cleaned between sites. Samples were preserved, labeled, kept at ~4 °C in ice-packed coolers, and transported to the laboratory within 24 hours. Field blanks and duplicate samples were included to ensure data reliability.

3.4. Extraction of Water Sample for PHCs Analysis

Liquid-liquid extraction, one liter (1 L) of the water samples were place into a separatory funnel with a glass stoppered using 50 ml of dichloromethane (DCM) as the extracting solvent. The separatory funnel were shaking vigorously for at least 10 min and the organic layer were allowed to separate clearly from the aqueous phase for a minimum of 15 minute. The lower organic layers were collected into a separate flask bottle. The extractions were repeated three times for each sample. Water residues were expelled from the organic layer by passing the extracts through funnel containing filter paper with sodium sulphate. The extract for each sample were concentrate using rotary evaporator with water bath at 35°C. Concentrated of the extracts were transferred to a pre-weighed bottle and evaporate to dryness [49, 53].

3.5. Silica Gel Clean-up and Separation of Water Samples for PHCs Analysis

The water extracts were transferred into a 10 mm ID × 30 cm chromatographic column packed with 10 g activated silica gel slurry with about 2 cm anhydrous sulphate layer on top. The columns were eluted with 20 ml of n-hexane to obtain the hydrocarbon fraction. The eluates were concentrated to about 2 ml with rotary evaporator at 30°C and evaporate to dryness [34].

3.6. Quality Assurance and Quality Control

All reagents and solvents used were of analytical and HPLC grades, correspondingly. Samples were routinely analyzed in duplicates with blanks and spike samples. Limit of detection (LOD) and limit of quantification (LOQ) for PHCs were estimate using replicate injections of a middle level calibration standard [43]. The LOD and LOQ were calculated by multiplying the “t” value at 99% confidence level with the instrument response and the values obtained. The precision of the instrument was estimate as the relative standard deviation (RSD) for the PHCs. The efficiency of the method was assessed from the recovered of the spike and unspike samples at different concentrations level for the water.

Quantification of individual hydrocarbon groups (C8–C40) was achieved by GC-MS using n-alkane standards to define carbon-number retention intervals, and peak areas were integrated accordingly. External calibration was performed using n-alkane standards (C8–C40). Known concentrations are injected. Peak area vs. concentration is plotted. This establishes the response factor used to convert sample peak areas into mass concentrations. The ranged for concentration of 0.1mg/L to 50 mg/L was used.

3.7. Carcinogenic Risk Assessment of PHCs in Water Samples

Carcinogenic risk (CR) values of PHCs in water via ingestion and dermal contact pathway was predicted from their chronic daily intake (CDI) obtained from the Eq. 1 predicted by [56].

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

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$$CR = CDI \times SF \quad (2)$$

Where:
CDI = Chronic daily Intake
C = Concentration
IR = Intake Rate
BW = Body Weight
EF = Exposure Factor
ED = Age Specific Exposure Duration
AT = Average Time

3.8. Instrumentation (GC-MS Analysis)

Concentrations of PHCs in water samples were determined using Shimadzu Gas Chromatography/Mass Spectrometer (GC-MS) QP 2010. Chromatographic separation was achieved by a BPX-5 capillary column (29.5 m×0.25 mm i.d., 0.2 µm film thickness) with a splitless injector and mass spectrometer detector. Helium were used as the carrier gas (0.98 ml min^{-1}). Samples were injected in the splitless mode with an injector temperature of 250°C. oven temperature was programme from 60°C to 240^0C (5 min hold), at 6 C min^{-1} and from 240°C to 300 °C (15 min hold), at 6°C min^{-1} rate [53].

Conclusion

This study confirms that water from Alau Dam, Konduga LGA, Borno State, is contaminated with petroleum hydrocarbons (PHCs), with concentrations ranging from 0.001 to 0.457 mg/L and higher levels near areas influenced by agricultural runoff and domestic discharges. Health risk assessment showed greater vulnerability among children, reflected in higher CDI values (1.12×10^{-5} to 8.43×10^{-3} mg/kg/day). While individual non-carcinogenic risks (HQ < 1) were generally within safe limits, cumulative Hazard Index values exceeded the acceptable threshold at several stations (0.87–3.46), indicating potential chronic health effects. Carcinogenic risk values ranged from 2.14×10^{-6} to 4.71×10^{-3}, with levels above USEPA benchmarks at stations S4, S6, and S9. Overall, PHC contamination poses significant ecological and public health risks, particularly for children reliant on the dam for domestic water use.

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