

Sources of Polycyclic Aromatic Hydrocarbons (PAHs) in Groundwater and Associated Health Risks to the Population: A Case of the Continental Terminal (CT) Aquifer in South-Eastern Côte d'Ivoire

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Abstract

Polycyclic aromatic hydrocarbons (PAHs) are emerging contaminants of concern in groundwater of Côte d'Ivoire's coastal zone, where rapid urbanisation and land-use changes have increased their release into the environment. This study investigated the occurrence, sources, and potential health risks of PAHs in groundwater from the unconfined Continental Terminal (CT) aquifer across the agricultural sectors of Dabou and Bonoua and the surrounding, urbanised sector of Abidjan. Concentrations of the 16 priority PAHs were analysed in 26 groundwater samples. Eight compounds were detected: fluorene (Flu), acenaphthylene (ACL), fluoranthene (FLR), pyrene (Pyr), benzo(b)fluoranthene [B(b)FL], benzo(a)pyrene [B(a)P], benzo(k)fluoranthene [B(k)FL], and indeno (1,2,3-cd)pyrene (InP). Total PAH concentrations ranged from 0.026 to 3.356 ng/L, with a predominance of low-molecular-weight PAHs, and remained well below the US EPA guideline value of 200 ng/L. Diagnostic ratio analysis revealed mixed petrogenic and pyrogenic origins, indicating contributions from petroleum-related activities and combustion processes. Human health risks were evaluated through ingestion and dermal exposure pathways. Non-carcinogenic haz-



ard indices (HI) and carcinogenic risks (CR) for both children and adults were significantly below accepted safety thresholds ($HI < 1$; $CR < 10^{-4}$), suggesting negligible current health risks. Nevertheless, continuous monitoring is recommended because of the persistence, mobility, and documented toxicity of PAHs in groundwater resources in a highly dynamic unconfined aquifer under an equatorial climate.

Keywords

Groundwater, Polycyclic Aromatic Hydrocarbons (PAHs),
Continental Terminal, Sources, Health Risks, Abidjan,
Western Africa Urban Area

1. Introduction

Groundwater pollution is now a major global issue, with significant consequences for human health and ecosystem services (Griebler & Avramov, 2015; Lapworth et al., 2022). Nearly a third of the world's population relies on groundwater for their drinking water supply (International Association of Hydrogeologists, 2010). Polycyclic aromatic hydrocarbons (PAHs) are highly toxic organic chemical pollutants that are widely present in the atmosphere, soil, water and sediments (Srogi, 2007). They are classified as priority pollutants and exhibit carcinogenic and mutagenic properties (Carmichael et al., 1997). In 1976, the U.S. Environmental Protection Agency (US EPA) listed 16 PAHs as priority pollutants (Qin et al., 2014). In recent decades, environmental contamination by PAHs has attracted the attention of numerous researchers worldwide (Montuori et al., 2016; Yang et al., 2013). In Africa, and particularly in West Africa, research into these pollutants is still in its infancy, with only a few recent studies conducted in Nigeria (Ore et al., 2023; Nwaozuzu et al., 2024), which indicate that in groundwater, sources of PAHs are linked to the combustion of fuel and biomass, posing high cumulative risks. In Côte d'Ivoire, studies conducted on surface waters (bays and lagoons) show significant concentrations of PAHs with pyrolytic and petrogenic sources (Kouakou et al., 2015; Gnonsonoro et al., 2023). The Ivorian sedimentary coastal basin, hosting the Continental Terminal (CT) aquifer, is the country's largest groundwater reserve and provides drinking water in the Greater Abidjan area. This aquifer is regularly replenished by rainfall. However, this resource is threatened by rapid urban growth (6 million inhabitants, or 21.5% of the Ivorian population in 2021, compared to 3 million in 1990 (INS, 2021)). This rapid population growth, combined with urban practices, is consequently leading to a decline in the quality and quantity of the CT's groundwater. Previous research conducted by Konan et al. (2022) in the atmosphere, rainwater and certain boreholes in the city of Abidjan has identified traces of organic pollution (PAHs) with associated health risks. Consequently, questions arise regarding the sources and health risks of the water that supplies, on a large scale, more than 6 million inhabitants living across the CT, taking into account rural areas

far removed from urban practices. The answer to these questions is provided by this work, which aims to identify the sources and health risks associated with PAHs in the CT groundwater, from the agricultural south-east (Bonoua) to the agricultural south-west (Dabou), passing through the heavily urbanised central area of Abidjan. Molecular diagnostic ratios were calculated to identify sources and assess health risks based on daily exposure doses via ingestion and dermal contact, and these were applied to all groundwater in the CT.

2. Materials and Methods

2.1. Study Area

The Dabou-Abidjan-Bonoua study area is located in the south-east of the Côte d'Ivoire sedimentary basin, between latitudes $5^{\circ}0'0''$ and $5^{\circ}40'0''$ N and longitudes $3^{\circ}15'0''$ and $4^{\circ}50'0''$ W, covering an area of 5543 km². Its southern boundary lies along the Atlantic Ocean (**Figure 1**). Over the period from 2004 to 2024, it recorded an average annual temperature of 26.3°C and annual rainfall of up to 1460 mm/year. The study area forms part of the southern forest landscape, characterised by a transition from open forest to dense rainforest (Girard et al., 1971). Rapid population growth, cash crops and excessive logging have led to a significant decline in forest cover since the 1950s. Today, only a few hectares remain, mainly comprising the Banco National Park and a few residual patches (Girard et al., 1971). In the District of Abidjan alone, the population has doubled from 3 million in 1990 to 6 million inhabitants in 2021 (INS, 2021), and the main source of drinking water for the District of Abidjan and its surroundings remains the unconfined aquifer of the sandy CT aquifer.

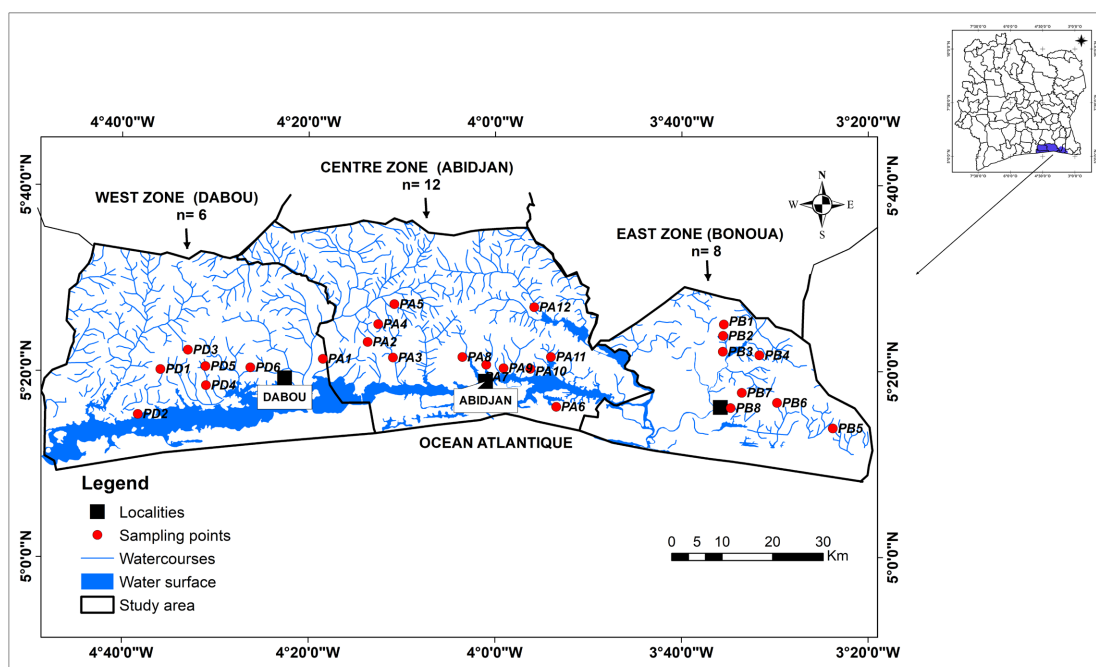


Figure 1. Study area and sampling sites for PAHs measurements.

2.2. Water Sampling and *in Situ* Measurements

Groundwater sampling was conducted from 19 to 29 March 2024 during the dry season. A total of 26 groundwater samples were collected from 26 piezometers belonging to the ONEP (Office National de l'Eau Potable, Abidjan) monitoring network for the CT aquifer. Each selected piezometer in the three considered areas (Dabou, Abidjan, and Bonoua; **Figure 1**) was sampled once during the field work. The selected piezometers were chosen because they are specifically designed to monitor groundwater within the Continental Terminal aquifer and are considered representative of the hydrogeological conditions of the studied groundwater. Their spatial distribution across the study area was intended to capture potential variations in PAHs occurrence and groundwater quality. The water was collected using a bailer, occasionally a messenger sampler for greater depths, and a 33-metre Tornado pump for shallower wells. These instruments enabled water to be collected at the specific depth, at the level of a screen level. Information on the screen position was provided by the technical data sheets drawn up during the installation of the piezometers by ONEP, which detail the geological formations traversed along with their depths. The pH (± 0.1), electrical conductivity ($\pm 2 \mu\text{S}/\text{cm}$) and temperature ($\pm 0.1^\circ\text{C}$) were measured *in situ* using a WTW-type multi-parameter meter. Amber glass bottles were used for water sampling for PAHs analysis. These bottles were rinsed several times with the raw water to be sampled. The water samples were kept at 4°C in a cool box until they reached the analysis laboratory.

2.3. Laboratory Analyses

PAHs concentrations were measured using gas chromatography coupled with a mass spectrometer (GC-MS) at the Vagny Lab laboratory in Côte d'Ivoire (ISO/IEC 17025:2017-accredited laboratory). The 16 priority PAHs identified by the U.S. Environmental Protection Agency (US EPA) were analysed: naphthalene (Nap), acenaphthylene (Acy), acenaphthene (ACL), fluorene (Flu), phenanthrene (Phe), anthracene (Ant), fluoranthene (FLR), pyrene (Pyr), benzo[a]anthracene (BaA), chrysene (Chr), benzo[b]fluoranthene (B[b]FL), benzo[k]fluoranthene (B[k]FL), benzo[a]pyrene (B[a]P), indeno[1,2,3-cd]pyrene (InP), dibenz[a,h]anthracene (D[a,h]A), and benzo[g,h,i]perylene (B[ghi]P). Groundwater samples were prepared using a liquid-liquid extraction protocol optimised for PAHs analysis. A 500 mL volume of water sample was taken, to which 100 mL of hexane was added, and the mixture was stirred for 60 minutes on a magnetic stirrer to facilitate the transfer of hydrophobic compounds into the organic phase. Phase separation was carried out using a separating funnel; the organic phase containing the PAHs was recovered and the aqueous phase was discarded. The organic extract was then dried over anhydrous sodium sulphate to remove any traces of residual water, thereby ensuring efficient recovery of the PAHs whilst minimising analytical losses.

PAHs were quantified using gas chromatography coupled with a mass spectrometer (GC-MS). The extracts were transferred to 0.5 mL vials for analysis, and

an internal standard, which is specific to the target compounds and naturally absent from the samples, was added to each extract to correct for variations arising from the extraction, preparation and injection stages. Compounds were identified on the basis of retention times and mass spectra, whilst quantification was carried out by comparison with the responses obtained from standard solutions. This method enabled the accurate and sensitive detection of PAHs present in the water samples.

A quality control and quality assurance procedure was applied to PAHs to ensure the reliability of the analytical results. Analytical blanks, duplicate analyses and recovery tests were used to verify the absence of contamination, as well as the accuracy and efficiency of the extraction method. Recovery rates ranged from 67.4% to 98.4%, with an analytical precision of less than 6% for repeated analyses. The calibration curves showed good linearity ($R^2 > 0.99$). The external laboratory did not provide method detection limits (LOD) or method quantification limits (LOQ), non-detected values were assigned a value of zero for the calculation of total PAH concentrations, diagnostic ratios, and health risk indices.

2.4. Molecular Profiling and Calculation of Molecular Diagnostic Ratios for Source Identification

The emission profile of polycyclic aromatic hydrocarbons (PAHs) from a given source is closely dependent on the processes that generate them (Manoli et al., 2004). In order to identify potential sources of PAHs in this study, the molecular profile and diagnostic ratios of PAHs were utilised. The molecular diagnostic ratios LMW/HMW and COMB/ Σ PAH were used to distinguish between petrogenic and pyrogenic PAHs sources. The LMW/HMW ratio provides information on the relative abundance of low- and high-molecular-weight PAHs, whereas COMB/ Σ PAH reflects the contribution of combustion-derived PAHs and is widely used for source apportionment studies. The ratio between low molecular weight (LMW) and high molecular weight (HMW) PAHs was calculated. Pyrogenic sources are generally characterised by a depletion of low molecular weight PAHs and an enrichment of high molecular weight PAHs, leading to LMW/HMW ratios below 1. In contrast, low molecular weight PAHs predominate in petrogenic sources, such as refined light petroleum products, resulting in LMW/HMW ratios greater than 1 (Wang et al., 2006; Zhang et al., 2008). Furthermore, the COMB/ Σ PAH ratio was used to distinguish between sources. Ratios < 0.3 indicate a petrogenic source, ratios between 0.3 and 0.7 suggest a mixed contribution, whilst ratios > 0.7 indicate a pyrogenic origin associated with combustion processes, particularly the combustion of fossil fuels (Ravindra et al., 2008; Iwegbue et al., 2019). However, these ratios should be interpreted with caution because environmental processes such as weathering, dissolution, biodegradation, and preferential loss of low-molecular-weight compounds may alter their original values, particularly when PAHs concentrations are very low. Table 1 presents the various ratios used.

Table 1. Diagnostic ratios and values for different processes.

HAP ratio	Values	Probable sources	References
$\Sigma\text{LMW}/\Sigma\text{HMW}$	<1	Petrogenic	Wang et al. (2006), Zhang et al. (2008)
	>1	Pyrogenic	
COMB/ ΣPAHs	<0.3	Petrogenic	Ravindra et al. (2008), Iwegbue et al. (2019)
	0.3 - 0.7	Combustion	
	>0.7	Combustion (wood, agricultural residues, fuels)	

2.5. Calculation of Health Risks

2.5.1. Non-Carcinogenic Risk

The daily exposure dose (DED) was calculated for both adults and children via ingestion and dermal contact (Equations (1) and (2)), as demonstrated in numerous studies on carcinogenic and non-carcinogenic risks (Adeniji et al., 2019; Konan et al., 2022; Myers et al., 2023; Sun et al., 2024).

$$DED_{ing} = \frac{C_i * IR * EF * ED}{BW * AT} \quad (1)$$

$$DED_{der} = \frac{C_i * SA * KP * ET * EF * ED * CF}{BW * AT} \quad (2)$$

where DED_{ing} and DED_{der} correspond, respectively, to the daily exposure doses ($\text{mg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$) via ingestion and dermal absorption; KP is the skin permeability coefficient in ($\text{cm}\cdot\text{h}^{-1}$); C_i is the concentration ($\text{ng}\cdot\text{L}^{-1}$) of the measured parameter in the water sample. **Table 2** summarises the various parameters and values used to calculate the exposure doses. For the purposes of risk characterisation, all exposure doses (DJE_{ing} and DJE_{der}), initially expressed in $\text{mg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$, were converted to $\text{mg}/\text{kg}/\text{day}$ using a conversion factor of 10^{-6} ($1 \text{ mg} = 10^6 \text{ ng}$), to ensure consistency with the toxicological reference values (RfD and CSF), which are expressed in $\text{mg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$.

Table 2. Parameters and values for calculating exposure doses (US EPA, 2006).

Parameter	Symbol	Unit	Adults	Children
Average daily water intake	IR	$\text{L}\cdot\text{d}^{-1}$	2.2	1.8
Exposure frequency	EF	$\text{d}\cdot\text{a}^{-1}$	365	365
Exposure duration	ED	a	30	6
Body weight avg	BW	kg	70	16
Average exposure duration	AT	d	10950	2190
Skin area	SA	cm^2	18000	6600
Average daily exposure time to water	ET	$\text{h}\cdot\text{d}^{-1}$	1	0.6
Conversion factor	CF	$\text{L}\cdot\text{cm}^{-3}$	0.001	0.001

The assessment of non-carcinogenic risk was carried out based on the hazard

quotient (HQ) and the hazard index (HI) (Amirah et al., 2013; Naveedullah et al., 2014). HQ highlights the toxicity that a single substance can cause at a given exposure level, whilst HI represents the toxic risk associated with potentially hazardous substances present in the same environmental medium and considered to be additive. HI is determined using Equations (3) and (4).

$$HQ_{ing} = \frac{DJE_{ing}}{RfD} \quad \text{and} \quad HQ_{der} = \frac{DJE_{der}}{RfD} \quad (3)$$

$$HI = \sum_{i=1} HQ_{ing} + HQ_{der} \quad (4)$$

where the RfD is the reference dose, i.e., daily dose to which populations could be continuously exposed throughout their lives without any appreciable risk of adverse effects (Alidadi et al., 2019). The RfD for each PAHs is presented in **Table 2**. Thus, according to the classification given by US EPA (2006), $HI < 1$ indicates an acceptable non-carcinogenic risk; conversely, $HI > 1$ indicates a higher probability of adverse health effects.

2.5.2. Carcinogenic Risk

Carcinogenic risk is defined by the US EPA (2006) as the additional probability that a person will develop cancer during their lifetime as a result of exposure to a probable carcinogen. For B(b)FL, B(a)P, B(k)FL and InP, the carcinogenic risks (CR) from ingestion and skin contact were calculated using Equations (5) and (6).

$$CR_{ing} = DJE_{ing} * CSF \quad \text{and} \quad CR_{der} = DJE_{der} * CSF \quad (5)$$

$$CR = \sum (CR_{ing} + CR_{der}) \quad (6)$$

where CSF is the slope factor specific to each carcinogenic PAHs. The CSF data for the PAHs considered in the calculation method are presented in **Table 3**.

The US EPA (2006) considers carcinogenic risks below 10^{-6} to be negligible. CRs between 10^{-6} and 10^{-4} are classified as intermediate while CR above 10^{-4} are considered unacceptable.

Table 3. RfD ($\text{mg}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$), Kp ($\text{cm}\cdot\text{h}^{-1}$) and CSF ($\text{mg}\cdot\text{kg}^{-1}\cdot\text{J}^{-1}$) data used in the method for calculating carcinogenic risks (US EPA, 2006).

HAP	B(b)FL	B(a)P	B(k)FL	InP	Flu	ACL	FLR	Pyr
Kp	1.2	1.2	1.18	1.9	0.214	0.155	0.36	0.51
CSF	0.73	7.3	0.73	0.73	-	-	-	-
RfD	0.03	0.03	0.03	0.03	0.04	0.06	0.04	0.03

3. Results and Discussion

3.1. Concentrations of PAHs in CT Groundwaters

Concentrations of the detected PAHs are presented in **Table 4**. Of the sixteen US EPA priority PAHs targeted in this work, only eight compounds were detected and quantified in the CT groundwater samples. These include Flu (fluoranthene), Acy (acenaphthylene), Flr (fluorene), Pyr (pyrene), B(b)Fl (benzo(b)fluoranthene),

B(a)P (benzo(a)pyrene), B(k)Fl (benzo(k)fluoranthene), and InP (indeno(1,2,3-cd)pyrene). The remaining priority PAHs were not detected in any of the analysed samples. Concentrations of light PAHs (Low Molecular Weight or LMW), notably Flu and ACL, range from 0.0013 to 3.2743 ng/L, with an average of 0.9164 ng/L and a standard deviation of 0.9370 ng/L in the water. Concentrations of heavy PAHs (High Molecular Weight or HMW), notably FLR, Pyr, B(b)FL, B(a)P, B(k)FL and InP, range from 0.0015 to 0.2290 ng/L, with a mean of 0.0489 ng/L and a standard deviation of 0.0611 ng/L. **Figure 2** shows the proportions of LMW and HMW in Dabou (western agricultural zone), Abidjan (central urbanised zone) and Bonoua (eastern agricultural zone). **Figure 2(a)** shows a predominance of light PAHs in the agricultural zone of Dabou (48%) compared to the agricultural zone of Bonoua (39%) and the urbanised zone of Abidjan (13%). **Figure 2(b)** shows a predominance of heavy PAHs in the agricultural zone of Bonoua (57%) compared to the urbanised zone of Abidjan (37%) and the agricultural zone of Dabou (6%).

Table 4. Laboratory analysis results and descriptive statistics.

	Localities	CODES	LMW				HMW			
			Flu	ACL	FLR	Pyr	B[b]FL	B[a]P	B[k]FL	InP
West	PALMAFRIQUE V2	PD1	0.0574	0.1314	0.0025	nd	0.0003	0.0005	0.0002	0.0013
	PETIT BADIEN	PD2	0.0159	0.1950	0.0002	nd	0.0004	0.0042	nd	0.0022
	CNRA OKPOYOU	PD3	0.1225	2.6000	0.0008	nd	0.0003	0.0006	0.0001	0.0017
	AGBAILLE	PD4	0.1841	2.1000	nd	nd	0.0017	nd	0.0003	0.0004
	CNRA PEPINIERE	PD5	0.1407	0.2750	0.0006	nd	nd	0.0004	nd	0.0005
	BOUBOURY	PD6	0.0549	0.8694	0.0014	0.0062	0.0001	0.0005	0.0005	0.0006
Centre	SONGON CH CAP	PA1	0.0828	0.2324	nd	0.0156	0.0034	0.0081	nd	nd
	WESSEKELEBO	PA2	0.6021	nd	nd	0.0229	0.0050	0.0034	nd	nd
	AYEWAHI SG	PA3	0.2335	nd	nd	0.0218	0.0031	0.0002	nd	nd
	ADONKOUA ST	PA4	0.1327	nd	nd	nd	0.0018	0.0022	0.0001	0.0002
	ATTINGUÉ	PA5	0.1270	nd	nd	0.0119	0.0004	0.0018	0.0002	0.0001
	AGBAGBOU	PA6	0.4141	2.8602	nd	0.0672	nd	0.0090	0.0032	0.0019
	BASSIN DU GOUROU	PA7	0.0407	0.3784	0.0001	0.0049	0.0007	0.0088	0.0028	nd
	BANCO MOSSIKRO	PA8	0.3499	1.3352	0.0005	0.0166	0.0012	0.0079	0.0032	0.0014
	UNIVERSITE COCODY	PA9	0.2499	0.0596	nd	0.2192	0.0083	0.0002	0.0009	0.0004
	M'BADON	PA10	0.0324	0.0918	nd	0.2257	0.0003	0.0002	0.0003	0.0002
	POL SCIENTIFIQ BING	PA11	0.0013	nd	nd	nd	0.0032	0.0006	0.0007	0.0206
	ANYAMAN DEBARQ	PA12	0.0267	nd	nd	0.0159	0.0034	0.0081	nd	nd
East	ONO SALCI	PB1	0.0132	0.3258	nd	0.0114	0.0004	0.0018	0.0002	0.0001
	ONO SITE 1	PB2	0.0341	2.2200	nd	0.0132	0.0018	0.0022	0.0001	nd
	SITE 4 ONO	PB3	0.0838	2.1700	nd	0.1222	0.0050	0.0034	nd	nd

Continued

ADOSSO CARREFOUR	PB4	0.2562	0.6450	nd	0.0702	0.0031	0.0002	nd	nd
AKOMIKRO	PB5	0.2518	1.7400	nd	0.0717	0.0041	0.0036	nd	nd
ABROBAKRO	PB6	0.3771	0.3922	nd	0.0941	0.0008	0.0052	nd	nd
TCHINTCHEBE	PB7	0.1764	0.5398	nd	0.0484	0.0001	0.0024	0.0012	nd
BONOUA	PB8	0.1329	0.4700	nd	0.0314	nd	0.0041	0.0009	0.0005
Max		0.6021	2.8602	0.0025	0.2257	0.0083	0.0090	0.0032	0.0206
Min		0.0013	nd	nd	nd	nd	nd	nd	nd
Mean		0.1613	0.7550	0.0002	0.0419	0.0019	0.0031	0.0006	0.0012
Standard Deviation		0.1447	0.90427	0.00056	0.06115	0.002	0.003	0.001	0.0039

Note: nd = not determined (below the limit of detection).

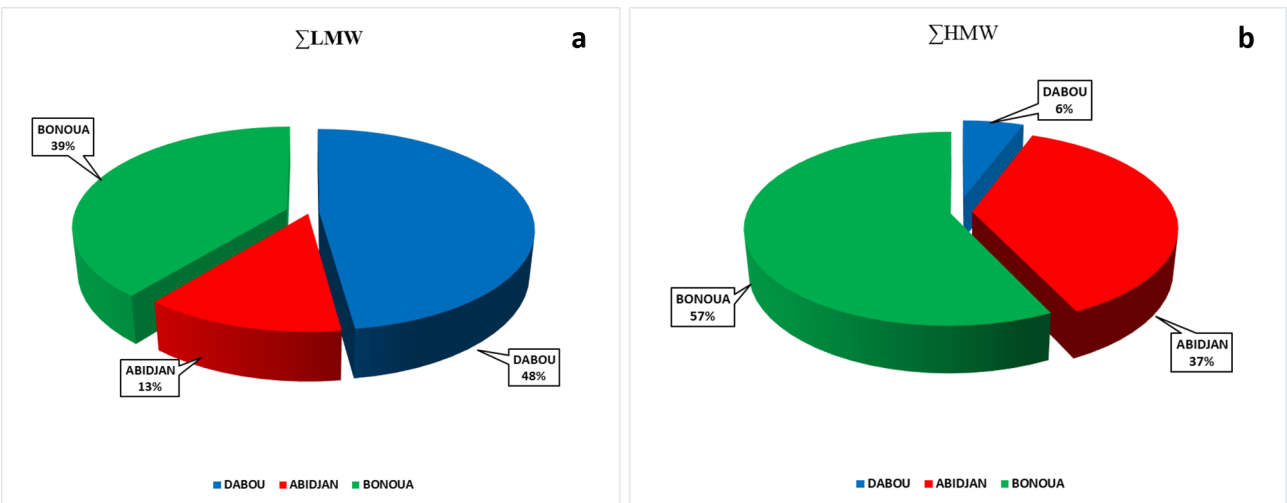


Figure 2. Proportion of LMW and HMW PAHs in the CT groundwater.

3.2. Source Identification Based on Molecular Profiles and Diagnostic Ratios

The molecular profile of LMW and HMW PAHs in the CT groundwater, shown in **Figure 3(a)**, indicates a significant contribution from light PAHs compared with heavy PAHs. The LMW/HMW ratios across the entire study area (PA1 to PB8) are almost all greater than 1, with proportions ranging from 49% to over 97%, except at points PA10, PA11 and PA12. These results predominantly indicate a petrogenic origin of PAHs in the CT linked to direct inputs of unburned hydrocarbons (fuel leaks, waste oils and lubricants, accidental spills), as demonstrated by *Yunker et al. (2002)* and *Tobiszewski and Namieśnik (2012)*. In tropical regions, heavy rainfall and high hydraulic conductivity of soils promote the leaching and rapid migration of light PAHs into groundwater during recharge, reinforcing their dominance (*Wilcke, 2000*). However, at data points PA10, PA11, and PA12, the dominance of heavy PAHs in the urbanised area of Abidjan suggests a pyrogenic origin, generally associated with combustion in urban environments,

notably road traffic, open-air waste incineration and the use of solid fuels (Yunker et al., 2002; Ravindra et al., 2008). The observed spatial variability in PAHs composition across the 3 selected areas can be related to differences in land use and hydrogeological conditions. Groundwater from Dabou and Bonoua, which are characterized by predominantly agricultural and peri-urban land use, generally exhibited higher proportions of LMW PAHs, suggesting diffuse petrogenic inputs associated with agricultural machinery, fuel storage, and local transportation activities. Furthermore, the unconfined nature of the aquifer and the permeable sandy formations of the Continental Terminal aquifer may facilitate the infiltration and transport of soluble low-molecular-weight PAHs into the groundwater. Conversely, the urbanized sites of Abidjan, particularly PA10, PA11, and PA12, displayed a greater contribution of HMW PAHs, reflecting the local influence of intense anthropogenic activities such as road traffic, industrial emissions, waste burning, and domestic combustion. These pyrogenic compounds are commonly associated with densely populated urban environments and may accumulate in groundwater through atmospheric deposition and soil leaching with infiltration into the vadose zone and groundwater.

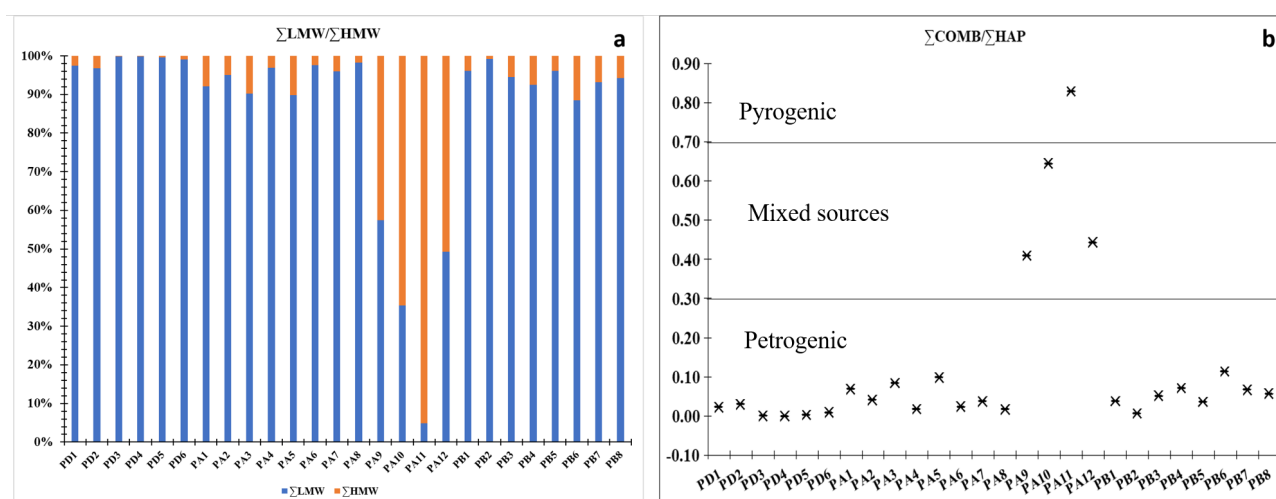


Figure 3. Molecular profile of LMW/HMW PAHs compounds in CT groundwater (a) diagnostic COMB/ Σ PAH ratio in CT groundwater (b) PDx are for Dabou area, PAx for Abidjan area and PBx for Bonoua area.

The COMB/ Σ PAH diagnostic ratio for the CT groundwaters shown in **Figure 3(b)** indicates that the main source of PAHs in the CT waters (agricultural and urbanised areas) is the petrogenic source, with a COMB/ Σ PAH ratio of less than 0.3. This predominance of petrogenic sources is likely linked to the use of hydrocarbons (fuels, waste oils, petrol or diesel leaks, and lubricants). A similar influence of petrogenic inputs has been reported in the work of Yunker et al. (2002), who show that low values of diagnostic PAHs ratios indicate a petrogenic origin (crude oil, fuel, waste oils). Intermediate values (0.3 - 0.7) indicate a mixed origin of PAHs, reflecting the overlap of petrogenic and pyrogenic sources (Sun et al., 2024; Ganiyu et al., 2024). In contrast, certain sites in urban areas exhibit high ratios (>0.7),

indicating a predominance of pyrogenic sources linked to combustion emissions (road traffic, open-air waste incineration). [Masih et al. \(2014\)](#) reported that pyrogenic sources dominate urban groundwater due to the combustion of fossil fuels. Although these diagnostic reports suggest that the inputs are primarily of petrogenic origin, their interpretation may be distorted by the weathering of the compounds and by low concentrations of PAHs, which may alter the signatures of the original sources.

3.3. Health Risk Assessment of CT Groundwater

The results of the assessment of non-carcinogenic and carcinogenic risks associated with the CT groundwater are presented in [Table 5](#). The results show that the non-carcinogenic and carcinogenic risks are below the guideline values recommended by the U.S. Environmental Protection Agency ([US EPA, 2006](#)). These guideline values correspond to a hazard index (HI) of 1 for the assessment of non-carcinogenic risk and a carcinogenic risk (CR) of 10^{-6} as the reference threshold for carcinogenic risk.

Table 5. Non-carcinogenic (HI) and carcinogenic risks (CR) in adults and children.

	Localities	CODES	Hazard index (HI)		Cancerogenic risk (CR)	
			Adults	Children	Adults	Children
West	PALMAFRIQUE V2	PD1	2.82E-07	8.61E-07	5.01E-10	1.48E-09
	PETIT BADIEN	PD2	2.68E-07	8.26E-07	1.55E-09	5.07E-09
	CNRA OKPOYOU	PD3	2.61E-06	8.30E-06	6.03E-10	1.78E-09
	AGBAILLE	PD4	2.31E-06	7.31E-06	4.10E-10	1.15E-09
	CNRA PEPINIERE	PD5	5.94E-07	1.82E-06	2.10E-10	6.56E-10
	BOUBOURY	PD6	9.74E-07	3.06E-06	3.51E-10	1.07E-09
Centre	SONGON CH CAP	PA1	6.37E-07	1.90E-06	2.40E-09	8.16E-09
	WESSEKELEBO	PA2	1.75E-06	5.12E-06	1.57E-09	5.01E-09
	AYEWAHI SG	PA3	8.00E-07	2.33E-06	5.36E-10	1.54E-09
	ADONKOUA ST	PA4	3.55E-07	1.05E-06	8.52E-10	2.78E-09
	ATTINGUÉ	PA5	4.41E-07	1.28E-06	5.31E-10	1.81E-09
	AGBAGBOU	PA6	4.27E-06	1.31E-05	3.01E-09	1.00E-08
	BASSIN DU GOUROU	PA7	5.67E-07	1.74E-06	2.57E-09	8.76E-09
	BANCO MOSSIKRO	PA8	2.29E-06	7.03E-06	2.83E-09	9.34E-09
	UNIVERSITE COCODY	PA9	2.82E-06	7.96E-06	1.59E-09	4.50E-09
	M'BADON	PA10	2.31E-06	6.47E-06	1.87E-10	5.59E-10
	POL SCIENTIFIQ BING	PA11	2.58E-07	7.16E-07	5.63E-09	1.57E-08
	ANYAMAN DEBARQ	PA12	2.99E-07	8.45E-07	2.40E-09	8.16E-09
East	ONO SALCI	PB1	4.45E-07	1.37E-06	5.31E-10	1.81E-09
	ONO SITE 1	PB2	2.19E-06	6.95E-06	8.05E-10	2.65E-09

Continued

SITE 4 ONO	PB3	3.33E-06	1.01E-05	1.57E-09	5.01E-09
ADOSO CARREFOUR	PB4	1.88E-06	5.59E-06	5.36E-10	1.54E-09
AKOMIKRO	PB5	2.88E-06	8.78E-06	1.47E-09	4.78E-09
ABROBAKRO	PB6	2.20E-06	6.44E-06	1.32E-09	4.63E-09
TCHINTCHEBE	PB7	1.39E-06	4.15E-06	7.54E-10	2.54E-09
BONOUA	PB8	1.08E-06	3.23E-06	1.20E-09	4.09E-09
Max		4.27E-06	1.31E-05	5.63E-09	1.57E-08
Min		2.58E-07	7.16E-07	1.87E-10	5.59E-10
Mean		1.51E-06	4.55E-06	1.38E-09	4.41E-09
Standard Deviation		1.11E-06	3.38E-06	1.19E-09	3.60E-09

3.3.1. Non-Carcinogenic Risks

Non-carcinogenic risks (HI) are low in both adults and children. In adults, non-carcinogenic risks range from 2.58×10^{-7} to 4.27×10^{-6} , with a mean of 1.51×10^{-6} and a standard deviation of 1.11×10^{-6} . The non-carcinogenic risks in children range from 7.16×10^{-7} to 1.31×10^{-5} , with a mean of 4.55×10^{-6} and a standard deviation of 3.38×10^{-6} . **Figure 4** shows the non-carcinogenic risks in adults and children. HI values being widely below 1 indicate the absence of non-carcinogenic health risks associated with PAHs in the groundwater studied. This is supported by several studies showing that low concentrations of PAHs generally result in HI values below the danger threshold ([Abdel-Shafy & Mansour, 2016](#)). However, the risks are higher for children compared to adults across the three areas concerned (Dabou, Abidjan and Bonoua). The higher risk for children compared to adults is explained by their lower body weight and higher water intake, as demonstrated by [Zhao et al. \(2026\)](#) in their assessment of risks in aquifer environments.

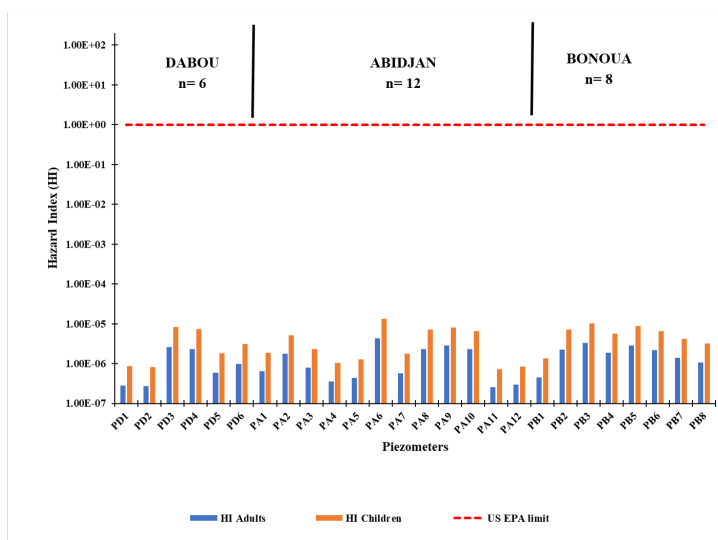


Figure 4. Spatial variability of non-carcinogenic risk in CT groundwater supplies among adults and children.

3.3.2. Carcinogenic Risks

The assessment of the carcinogenic risk in the groundwater of the agricultural areas of Dabou and Bonoua, as well as that of the urbanised area of Abidjan, is presented in **Table 4**. The carcinogenic risk for adults ranges from 1.78×10^{-10} to 5.63×10^{-9} , with a mean of 1.38×10^{-9} and a standard deviation of 1.19×10^{-9} . For children, the risk ranges from 5.59×10^{-10} to 1.57×10^{-8} , with a mean of 4.41×10^{-9} and a standard deviation of 3.60×10^{-9} . **Figure 5** shows the carcinogenic risks for adults and children. The risks remain below 10^{-6} and, like HI, they are higher in children. These results show that the carcinogenic risks associated with PAHs in the CT groundwater remain generally below the 10^{-6} threshold, indicating a low level of risk according to **US EPA (2006)** criteria. This trend was noted by **Montuori et al. (2023)**, who showed that carcinogenic risks associated with PAHs in groundwater can remain within the negligible range ($<10^{-6}$) in several contaminated hydrogeological contexts. The negligible risk for both children and adults confirms that the PAHs in the studied waters likely originate from diffuse contamination at low concentrations, according to the work of **Ravindra et al. (2008)**. Although the risks remain negligible in both adults and children, children face higher risks than adults. This is due to their higher daily dose relative to body weight. The work of **Wu et al. (2016)** reports that children exhibit increased sensitivity to PAHs through the ingestion of contaminated water.

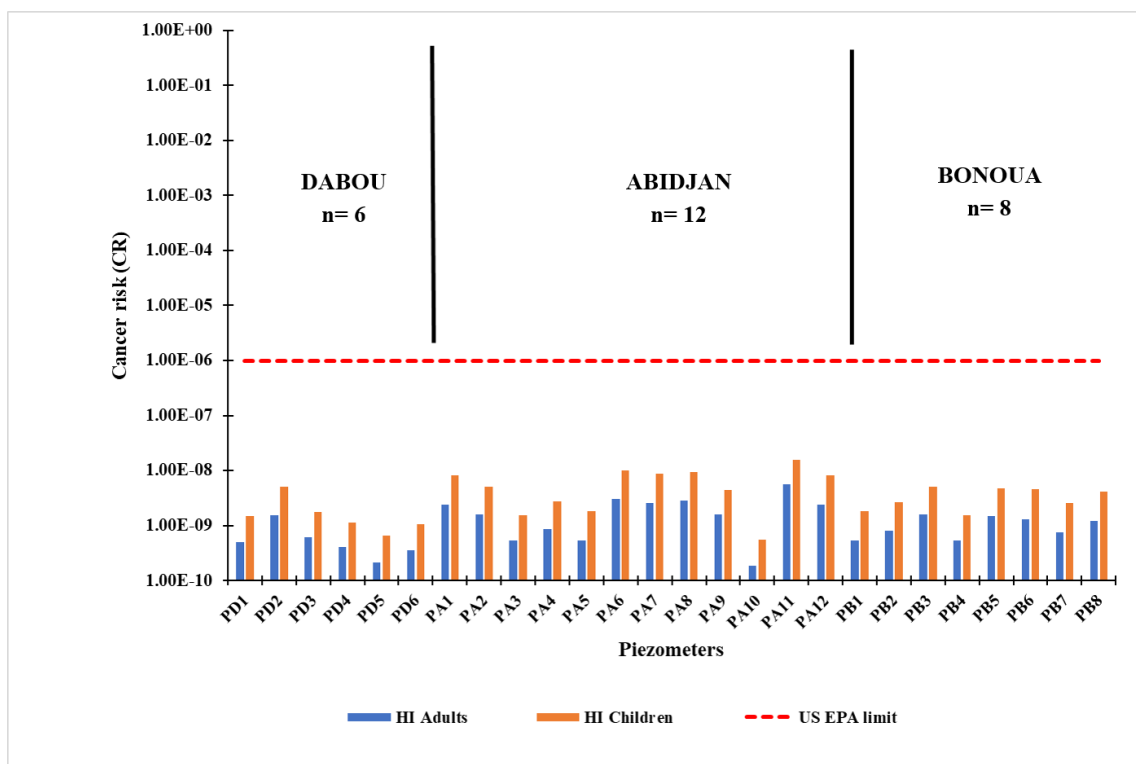


Figure 5. Spatial variability of carcinogenic risk in CT water supplies among adults and children.

A limitation of this study is that method detection limits (LOD) and method

quantification limits (LOQ) were not available from the external analytical laboratory. Consequently, compounds reported as “nd” (not detected) were assigned a value of zero in the calculation of summary statistics, diagnostic ratios, and health risk estimates. This approach may have resulted in a slight underestimation of the total PAHs concentrations and the associated health risk estimates. Nevertheless, this limitation does not affect the interpretation of the detected PAHs, which constitute the basis of the environmental and health risk assessment presented in this study.

4. Conclusion

This study has revealed the presence of PAHs in the order of ng per liter in the groundwater of the Continental Terminal in the Dabou, Abidjan and Bonoua areas, influenced by human activities and land-use patterns. The research showed a predominance of light PAHs and identified two main sources of groundwater contamination by these PAHs. These are the petrogenic source (the dominant source) and the pyrogenic source. Although the measured concentrations remain below US EPA standards, their presence indicates diffuse contamination of the CT’s groundwater beneath Dabou, Abidjan and Bonoua. The health risk assessment indicates low levels of risk for both non-carcinogenic and carcinogenic effects in adults and children. However, given the recognised toxicity of PAHs and their persistent nature, regular monitoring of groundwater remains necessary. This study provides an important knowledge base for the management of the CT groundwater, as well as for the health protection and prevention of the populations supplied by this vital resource.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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