



(RESEARCH ARTICLE)



POLYCYCLIC AROMATIC HYDROCARBON (PAHS) CONTAMINATION IN TEGUERE RIVER, KORHOGO, NORTHERN CÔTE D'IVOIRE: CONTAMINATION LEVELS, PROBABLE SOURCES AND ENVIRONMENTAL IMPLICATIONS

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ABSTRACT

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic contaminants that pose significant environmental and public health. The objective of this study was to assess the risks associated with the presence of polycyclic aromatic hydrocarbons (PAHs) in the Teguere River. Ten water samples were collected from upstream and downstream locations and analyzed for the 16 priority PAHs using high-performance liquid chromatography (HPLC). Eight PAHs were quantified, while the remaining compounds were below detection limits. The mean concentrations of Σ8 PAHs were 0.3320 µg/L upstream and 0.3188 µg/L downstream, with low-molecular-weight PAHs constituting the dominant fraction. Phenanthrene was the predominant PAH upstream (0.0680 µg/L), whereas naphthalene was most abundant downstream (0.0620 µg/L). According to the SEQ-Eau V2 classification, the quantified PAHs indicated water quality ranging from very good to moderate. Diagnostic ratios, including Flt/(Pyr + Flt), Flt/Pyr, and LMW/HMW, indicated mixed pyrogenic and petrogenic sources. The non-carcinogenic hazard indices associated with dermal exposure were substantially below 1 for both adults and children, suggesting no appreciable non-carcinogenic risk under the exposure

assumptions considered. However, the estimated total dermal cancer risks ranged from 2.16×10^{-3} to 3.91×10^{-3} , exceeding the commonly accepted risk range of 10^{-6} to 10^{-4} . Benzo[a]pyrene and benzo(b)fluoranthene were the primary contributors to carcinogenic risk. The total toxic equivalent quotient (TEQ) was 0.009904 $\mu\text{g/L}$ upstream and 0.010123 $\mu\text{g/L}$ downstream, while the mutagenic equivalent quotient (MEQ) was 0.013895 and 0.015176 $\mu\text{g/L}$, respectively. Regular PAH monitoring and reduced anthropogenic inputs are needed to limit dermal exposure, particularly among children.

Keywords: Korhogo, Teguer river, Polycyclic aromatic hydrocarbons, Human health, Risk Assessment.

1 INTRODUCTION

Surface waters located in urban and peri-urban environments are particularly vulnerable to contamination by organic and inorganic pollutants originating from domestic wastewater, industrial discharges, road runoff, petroleum-related activities, atmospheric deposition and combustion processes. Among these contaminants, polycyclic aromatic hydrocarbons (PAHs) have received considerable scientific attention because of their persistence, hydrophobicity, widespread environmental distribution and potential adverse effects on human health and aquatic ecosystems [1] and [2]. PAHs are a group of organic compounds composed of two or more fused aromatic rings and are commonly associated with both natural and anthropogenic processes [3] and [4]. PAHs can be released into the environment through natural processes, including volcanic activity, forest fires and the diagenesis of organic matter, but anthropogenic activities generally constitute the major sources in populated and industrialized areas [4]. Important anthropogenic sources include the incomplete combustion of fossil fuels, biomass and coal, vehicle exhaust emissions, petroleum handling and spills, waste incineration, industrial processes and the use of petroleum-derived products [5]. Once released into the environment, PAHs undergo complex transport and transformation processes. Their environmental fate is strongly influenced by their molecular structure and physicochemical properties [6]. The occurrence of PAHs in freshwater systems is therefore influenced not only by the magnitude and nature of pollution sources but also by hydrological conditions, land use, organic matter content, suspended solids and the physicochemical characteristics of individual PAHs [6]. The presence of PAHs in aquatic environments is of particular concern because several compounds exhibit toxic, mutagenic, genotoxic and carcinogenic properties. Among the PAHs, benzo[a]pyrene (BaP) is one of the most extensively studied carcinogenic compounds and is commonly used as a reference compound for evaluating the carcinogenic potential of PAH mixtures [7]. In aquatic environments, PAHs may also affect microorganisms, aquatic plants, invertebrates and fish, thereby creating potential ecological consequences in contaminated freshwater systems. In Côte d'Ivoire, rapid urbanization and the intensification of anthropogenic activities have increased pressure on freshwater resources, particularly in rapidly developing urban centers. Korhogo, located in northern Côte d'Ivoire, has experienced significant urban expansion accompanied by increasing road traffic, mechanical workshops, commercial activities and petroleum use. These activities may constitute potential sources of hydrocarbon-derived contaminants that can reach surface waters through atmospheric deposition, accidental spills, wastewater discharge and urban runoff. The Tégouéré River and its watershed are therefore of particular interest because the watercourse crosses areas influenced by agricultural activities and increasing urbanization. Despite the environmental importance of the Tégouéré River for the Korhogo area, information on the occurrence, distribution and probable sources of PAHs in its surface waters remains limited. Accordingly, the present study aimed to assess the risks associated with the presence of polycyclic aromatic hydrocarbons (PAHs) in the Tégouéré River in Korhogo, northern Côte d'Ivoire.

2 MATERIAL AND METHODS

2.1 Study area description

Korhogo town is located 635 kilometres from Abidjan, Côte d'Ivoire State's capital. It lies between latitude 9.3° North and longitude 5.40° West, at an elevation of 380 metres above sea level [8]. The annual total rainfall averages are 1 200 and 1 400 mm, respectively. The average temperature is 26.7°C [9] and is a savannah. The study area experiences a rainy season and dry season. Teguer River flows through the city and originates from the base of close to mount Korhogo (Figure 1). river is mainly used for agricultural and other anthropogenic activities. Teguer River accumulates discharged wastes from different anthropogenic sources, thus affecting the water quality.

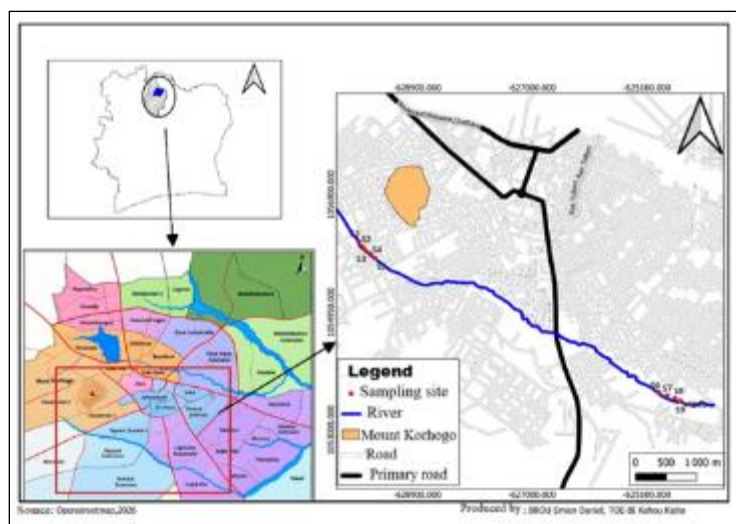


Figure 1: Location map of the study area and water sampling sites.

2.2 Sampling collection and Determination of PAHs in water samples

2.2.1 Sampling collection

A total of ten surface water samples were randomly collected from the Teguéré River in June 2026 (Figure 1), at two sampling stations, namely the upstream station ($n = 5$) and the downstream station ($n = 5$). At each station, ten water samples were collected in the morning between 6:00 a.m. and 10:00 a.m. Water samples were collected from the water column at depths ranging from 0.5 to 1.5 m at each station using a 1-L Niskin bottle. Before each sampling, the bottle was rinsed twice with the water to be collected to minimize potential contamination. After collection, the water samples were transferred, into 1-L Plastic bottles. The bottles were then hermetically sealed and stored at approximately 4 °C until laboratory analysis. The sampling points were georeferenced using a Garmin GPS device (Tableau 1). All sampling, handling, and preservation procedures were conducted in accordance with the recommendations of standard AFNOR [10].

Table 1: Sampling sites and their geographical coordinates

Stations	Latitude	Longitude
S1	9.444280°	-5.658186°
S2	9.443477°	-5.657626°
S3	9.443042°	-5.657272°
S4	9.442508°	-5.656543°
S5	9.441828°	-5.655771°
S6	9.422022°	-5.613537°
S7	9.421579°	-5.612296°
S8	9.421183°	-5.611148°
S9	9.420832°	-5.610356°
S10	9.420360°	-5.609018°

2.2.2 Determination of PAHs in water samples

The sixteen PAHs classified as priority pollutants by the US Environmental Protection Agency [11] were analyzed in the water samples. These compounds included Acenaphthene (Ace), Acenaphthylene (Acpt), Anthracene (Atc), Benzo[a]anthracene (Baa), Benzo[a]pyrene (Bap), Benzo[b]fluoranthene (Bbf), Benzo[g,h,i]perylene (B(g,h,i)P), Benzo[k]fluoranthene (Bkf), Benzo[j]fluoranthene (BjF), Chrysene (Chry), Fluoranthene (Flt), Fluorene (Flr), Naphthalene (Nap), Phenanthrene (Phen), Pyrene (Pyr), and Indeno[1,2,3-cd]pyrene (I(1,2,3-c,d)P). In the laboratory, polycyclic aromatic hydrocarbons (PAHs) were extracted and purified from the water samples according to the analytical method described by [12]. To prevent cross-contamination, all equipment used during sampling and analysis

was thoroughly decontaminated with appropriate cleaning agents. PAHs were extracted from water samples via liquid-liquid extraction with 100 mL of dichloromethane. The resulting organic extract was concentrated using a rotary evaporator and filtered through Whatman filter paper. The filtrate was transferred to a 2-L separatory funnel and dried over anhydrous sodium sulfate. Further concentration was achieved under a gentle stream of nitrogen at 40 °C to a final volume of 0.5 mL. Purification was performed using a glass chromatography column containing 5 g of deactivated alumina and 1 g of anhydrous sodium sulfate. The column was preconditioned with approximately 10 mL of cyclohexane. When the solvent reached the sodium sulfate layer, the flow was stopped, and the extract was loaded onto the column. PAHs were eluted with 40 mL of hexane, and the eluate was concentrated under nitrogen to a final volume of 0.5 mL. The purified extract was transferred to 1.5-mL amber glass vials for analysis by high-performance liquid chromatography (HPLC). Limits of detection (LOD) and quantification (LOQ) were determined according to the procedure described by [13]. The overall LOD and LOQ were 0.005 $\mu\text{g L}^{-1}$ and 0.010 $\mu\text{g L}^{-1}$, respectively. For benzo[a]pyrene (BaP), dibenzo[a,h]anthracene (DahA), and indeno[1,2,3-cd]pyrene (IcdP), the LOQ was 0.005 $\mu\text{g L}^{-1}$.

2.3 Determination of the origin

Proper management of PAH emissions requires identifying their sources as precisely as possible. PAHs typically originate from four main sources: geogenic, petrogenic, pyrolytic, and biogenic [14]. Diagnostic ratios are widely used to infer their likely sources in eco systems [15] and [16]. For Flt/(Flt + Pyr) ratio was used as a molecular diagnostic ratio to identify the potential sources of PAHs. Values <0.40 are indicative of petroleum or oil spill sources, values between 0.40 and 0.50 imply petroleum combustion, whereas values >0.50 are associated with biomass combustion [17]. The LMW/HMW ratio further aids source characterization: ratios >1.0 are typically linked to petrogenic origins, whereas < 1.0 suggests pyrogenic sources [18]. Following the classification proposed by [19] The ratio of fluoranthene / pyrene (Flur/Py) > 1 indicates pyrogenic origin, while Flur/Py < 1 indicates petrogenic origin.

2.4 Determination of contamination levels of water

The SEQ-Eau V2 guidelines [20] are utilized to define water quality based on the presence of polycyclic aromatic hydrocarbons (PAHs), including the 16 priority PAHs identified by the [11]. These guidelines were employed for this purpose in the present study (Table 2).

Table 2: Quality of the waters according to SEQ-Eau V2 guidelines

PAHs	Very good / Blue ($\mu\text{g/L}$)	Good / Green ($\mu\text{g/L}$)	Moderate / Yellow ($\mu\text{g/L}$)	Poor / Orange ($\mu\text{g/L}$)
Naphthalene	≤ 0.19	$>0.19-1.90$	$>1.90-460$	>460
Acenaphthene	≤ 0.07	$>0.07-0.70$	$>0.70-160$	>160
Fluorene	≤ 0.03	$>0.03-0.30$	$>0.30-77$	>77
Phenanthrene	≤ 0.011	$>0.011-0.11$	$>0.11-27$	>27
Fluoranthene	≤ 0.0024	$>0.0024-0.024$	$>0.024-6$	>6
Pyrene	≤ 0.0024	$>0.0024-0.024$	$>0.024-6$	>6
Benzo(b)fluoranthene	≤ 0.0001	$>0.0001-0.001$	$>0.001-0.30$	>0.30
Benzo(a)pyrene	≤ 0.00003	$>0.00003-0.00030$	$>0.00030-0.08$	>0.08

2.5 Human health risk assessment (HHRA)

Assessment of health risk to humans is achieved by calculating the possibility of any severe health effects coming from the exposure of an individual to carcinogenic and/or non-carcinogenic substances over a particular period of time [21] and [22]. This study evaluates the short- and long-term human health risks associated with the presence of PAHs in Teguere river, considering frequently observed anthropogenic activities. market gardening is practiced along the water body's banks. Children also use this Teguere river for bathing. Therefore, this study assessed the health risks related to PAH presence in this lacustrine system for children and adults, accounting for their specific activities. Only dermal contact risks were considered, as inhalation and ingestion risks directly from the water body were deemed negligible.

2.5.1 Non-carcinogenic risk assessment

For non-carcinogenic risks associated with PAHs in the water samples collected from the study area, average daily dosage by dermal contact (ADD_{der}) in mg/kg/day was calculated using Eq. (1).

$$ADD_{der} = \frac{C_i \times SA \times K_p \times ET \times EF \times ED \times CF}{BW \times AT_{nc}} \quad (1)$$

The chronic (average) daily intake obtained from Eq. (2) and Eq. (3) were used to obtain the hazard index for non-carcinogenic TPHs as shown below [23] et [24].

$$HQ_i = \frac{ADD_{der i}}{RfD_{der i}} \quad (2)$$

$$HI = \sum HQ_i \quad (3)$$

When HI (HQ) < 1, no carcinogenic risk is identified in relation to the sum of pollutants (or a specific pollutant). Conversely, when HI (HQ) > 1, the analyzed matrix appears to present a potential hazard to humans [25], [26] et [27].

2.5.2 Carcinogenic risk assessment

The carcinogenic risks in this study were determined by the estimation of LADD (mg/kg/day), incremental lifetime cancer risk (ILCR) and risk index (RI) in the water samples (Table 3). The expressions for ILCR_{derm} for a single PAH and RI_{derm} for a mixture of PAHs are then established as follows [28] et [29]:

$$ILCR_{der i} = LADD_{der i} \times CSF \quad (4)$$

$$RI = \sum_{i=1}^n ILDR_{der i} \quad (5)$$

If RI is less than 10⁻⁶, it is considered negligible ; if it is more than 10⁻⁴, there is cause for significant concerns [30].

Table 3: Exposure variables used for the assessment of human health risk

Parameter	Meaning	Adult	Child	Unit	References
EF	Exposure frequency	250	250	days	[31]
ED	Exposure duration	30	6	years	[31]
BW	Body weight	70	15	Kg	
AT _{nc}	Average time for non-carcinogenic	ED x 365=10950	ED x 365= 2190		[31]
AT _c	Average time for carcinogenic	25 550	25 550		[31]
SA	Skin-surface area	18 000	6 600	Cm ²	[31]
K _p	dermal permeability coefficient	Nap: 0,069; Phe: 0,270; Flt: 0,360; Ace: 0,135; Flu: 0,178; BbF: 1,20; BaP: 1,20; Pyr: 0,460		(cm/h)	[26] et [27]
ET	exposure time during work event	0,58	1	H/day	[31]
CF	conversion factor	1.00E-3		L/cm3	[31]

CSF	the cancer slope factor for individual congener	BbF : 0,73; BaP : 7,30; Nap: 0,0073; Phe: NA; Flt: 0.0073; Ace: 0.0073; Flu: 0.0073; Pyr: 0.073	mg/kg/day	[23] et [27]
RfD _{derm}		Nap: 0,02**; Phe: NA; Flt: 0.04**; Ace: 0.02**; Flu: 0.04**; BbF 0.03**; BaP: 0.03**; Pyr: 0.03**	mg/kg/day	[32]

2.5.3 Evaluation of toxic and mutagenic equivalent quotients of PAHs

The toxic equivalent quotient (TEQ) or carcinogenic potential of the high molecular weight PAHs and mutagenic equivalent quotient (MEQ), otherwise referred to as the capacity of each congener to cause modification in human's DNA (deoxyribonucleic acid). They were calculated by multiplying their individual toxic equivalent factor (TEF) and mutagenic equivalent factor (MEF) with the mean concentration of each PAH in the sediment samples as shown in Eqs. (6) and (7) [33] et [34].

$$TEQ = \sum c_i \times TEF_i \quad (6)$$

$$MEQ = \sum c_i \times MEF_i \quad (7)$$

where C_n = concentration of the individual PAH congener (n) in the mixture, and TEF_i = toxic equivalence factor for individual PAH congener (n). MEF_i = mutagenic equivalent factor for individual PAH congener (n)

2.5.4 Statistical Analysis

Statistical analysis of the water sample data was conducted using XLSTAT 2019.2.2. Descriptive statistics, such as mean, standard deviation (SD), coefficient of variation (CV), minimum, and maximum, were calculated to characterize the distribution and variability of the measured parameters. Pie charts were also generated with XLSTAT 2019.2.2 to illustrate the relative distribution of the data and support interpretation of the results.

3 RESULTS AND DISCUSSION

The concentrations of the 16 USEPA priority PAHs were determined in the Teguere River. The results of the analysis are presented in Table 3. Mean concentrations, standard deviations, maximum and minimum values, and coefficients of variation (CV%) were calculated for both individual PAHs and total PAH levels at each location. In addition, composition profiles, source apportionment using diagnostic ratios, incremental lifetime cancer risk (ILCR), and non-cancer risk (NCR) were evaluated to provide a comprehensive understanding of the sources, health risks, and potential impacts of PAH contamination in these areas (upstream and downstream of the river).

3.1 PAHs Abundance in the waters from these surface waters

Polycyclic aromatic hydrocarbons (PAHs) in the Teguere river are widely recognized as indicators of environmental contamination (Table 4 and 5) and potential human exposure [32]. The Teguere river samples recorded different PAH concentrations for both locations (Upstream and downstream), confirming the pollutants' ubiquitous nature [35]. Acenaphthylene (Acy), Anthracene (Ant), Benzo[a]anthracene (BaA), Chrysene (Chr), Benzo[k]fluoranthene (BkF), Dibenzo[a,h]anthracene (DahA), and Indeno[1,2,3-cd]pyrene (IndP) were not detected in these waters during the study period. These values were below the limit of detection (LOD) in the experiment. Descriptive statistics showed that PAH profiles were comparable between the downstream and upstream sections of the watercourse. The mean concentration of $\Sigma 8$ PAHs was 0.3320 $\mu\text{g/L}$ upstream and 0.3188 $\mu\text{g/L}$ downstream, indicating only a slight increase in the overall PAH burden upstream. The similar concentrations between the two sections suggest that PAH contamination was not exclusively associated with upstream activities. Rather, the observed distribution may reflect the combined influence of background inputs, diffuse and localized anthropogenic sources, atmospheric deposition, and runoff [36]. The PAH distribution was dominated by low-molecular-weight PAHs (LMW-PAHs). Their mean concentrations were 0.2033 $\mu\text{g/L}$ upstream and 0.1823 $\mu\text{g/L}$ downstream. This predominance indicates that the lighter PAH congeners largely influenced the contamination profile. Among the LMW compounds, phenanthrene showed the highest mean concentration upstream (0.0680), followed by naphthalene (0.0580) and acenaphthene (0.0453). Downstream, naphthalene had the highest mean concentration (0.0620), followed by phenanthrene (0.0520) and acenaphthene (0.0403). The predominance of LMW-PAHs may be associated with petrogenic inputs and low-temperature combustion processes, since these compounds are generally more volatile and water-soluble than high-molecular-weight congeners [37]. Possible sources include petroleum-derived inputs, domestic activities, runoff, combustion emissions, and other diffuse anthropogenic sources [6]. However, source attribution should ideally be supported by diagnostic ratios before a specific source is conclusively assigned. The MMW-PAHs represented the second most important group, with mean

concentrations of 0.0780 upstream and 0.0820 downstream. The concentrations were therefore very similar between the two sections. Fluoranthene and pyrene were the principal contributors to this group. The relatively low CV values for MMW-PAHs (29.24% upstream and 27.81% downstream) indicate comparatively moderate spatial variability [38]. The HMW-PAHs exhibited lower mean concentrations than the LMW and MMW fractions, with 0.0507 upstream and 0.0546 downstream. Despite their lower absolute concentrations, HMW-PAHs are environmentally important because several congeners in this group, particularly benzo[a]pyrene, benzo[b]fluoranthene, and benzo[g,h,i]perylene, are associated with carcinogenic and/or mutagenic effects [39]. In the study, benzo[a]pyrene, benzo[b]fluoranthene, and benzo[g,h,i]perylene were consistently detected. [40] stated that HMW-PAHs are mainly a result of pyrolytic processes. The PAHs found in the Teguere river samples comprised low- and high molecular weight PAHs, which were reported previously [41]. The highest individual mean concentration upstream was observed for phenanthrene (0.0680), whereas downstream naphthalene (0.0620) was the dominant quantified PAH. Conversely, benzo[a]pyrene showed relatively low mean concentrations (0.0064 upstream and 0.0066 downstream), but its presence is nevertheless important from a toxicological perspective because of its recognized carcinogenic potential [39]. The CV values indicate different degrees of spatial variability among the compounds. Phenanthrene showed particularly high variability, with CV values of 64.44% upstream and 100.30% downstream, suggesting substantial heterogeneity among sampling sites [38]. Benzo[b]fluoranthene also exhibited relatively high variability (63.25% upstream and 71.28% downstream). In contrast, benzo[a]pyrene showed comparatively low variability, with CVs of 17.82% upstream and 17.28% downstream, indicating a more homogeneous distribution. Overall, the results indicate that LMW-PAHs constituted the dominant fraction of the PAH contamination, followed by MMW- and HMW-PAHs. The slightly higher $\Sigma 8$ PAH concentration upstream does not by itself demonstrate an upstream pollution source because the downstream concentration was also substantial. The similarity between the two zones suggests that PAHs may originate from multiple diffuse and/or continuous sources throughout the studied watercourse, rather than from a single localized source [6]. Further source-apportionment analysis using diagnostic ratios would strengthen this interpretation.

Table 4: Polycyclic Aromatic Hydrocarbons (PAHs) mean concentration of water samples in the upstream.

Parameter	Mean	Min	Max	SD	CV (%)
Naphthalene (Nap)	0.0580	0.0300	0.0900	0.0228	39.32
Acenaphthylene (Acy)	ND	ND	ND	ND	—
Acenaphthene (Ace)	0.0453	0.0352	0.0528	0.0065	14.32
Fluorene (Flr)	0.0320	0.0200	0.0400	0.0084	26.15
Phenanthrene (Phe)	0.0680	ND	0.1200	0.0438	64.44
Anthracene (Ant)	ND	ND	ND	ND	—
Fluoranthene (Flt)	0.0440	0.0300	0.0600	0.0114	25.91
Pyrene (Pyr)	0.0340	0.0200	0.0500	0.0114	33.53
Benzo[a]anthracene (BaA)	ND	ND	ND	ND	—
Chrysene (Chr)	ND	ND	ND	ND	—
Benzo[b]fluoranthene (BbF)	0.024	ND	0.0400	0.0152	63.25
Benzo[k]fluoranthene (BkF)	ND	ND	ND	ND	—
Benzo[a]pyrene (BaP)	0.0064	0.0050	0.0080	0.0011	17.82
Dibenzo[a,h]anthracene (DahA)	ND	ND	ND	ND	—
Benzo[g,h,i]perylene (BghiP)	0.0203	0.0133	0.0274	0.0054	26.50
Indeno[1,2,3-cd]pyrene (IndP)	ND	ND	ND	ND	—
LMW PAHs	0.2033	0.1552	0.2784	0.0494	24.28
MMW PAHs	0.0780	0.0500	0.1100	0.0228	29.24
HMW PAHs	0.0507	0.0183	0.0754	0.0213	41.96
$\Sigma 8$ PAHs	0.3320	0.2236	0.4639	0.0862	25.97

Table 5: Polycyclic Aromatic Hydrocarbons (PAHs) mean concentration of water samples in the downstream.

Parameter (µg/l)	Mean	Min	Max	SD	CV (%)
Naphthalene (Nap)	0.0620	0.0300	0.0900	0.0228	36.78
Acenaphthylene (Acy)	ND	ND	ND	ND	—
Acenaphthene (Ace)	0.0402	0.0333	0.0516	0.0085	21.08
Fluorene (Flr)	0.0280	0.0200	0.0400	0.0084	29.88
Phenanthrene (Phe)	0.0520	ND	0.1200	0.0522	100.30
Anthracene (Ant)	ND	ND	ND	ND	—
Fluoranthene (Flt)	0.0460	0.0300	0.0600	0.0114	24.79
Pyrene (Pyr)	0.0360	0.0200	0.0500	0.0114	31.67
Benzo[a]anthracene (BaA)	ND	ND	ND	ND	—
Chrysene (Chr)	ND	ND	ND	ND	—
Benzo[b]fluoranthene (BbF)	0.0274	ND	0.0500	0.0196	71.28
Benzo[k]fluoranthene (BkF)	ND	ND	ND	ND	—
Benzo[a]pyrene (BaP)	0.0066	0.0050	0.0080	0.0011	17.28
Dibenzo[a,h]anthracene (DahA)	ND	ND	ND	ND	—
Benzo[g,h,i]perylene (BghiP)	0.0205	0.0130	0.0273	0.0055	26.68
Indeno[1,2,3-cd]pyrene (IndP)	ND	ND	ND	ND	—
LMW PAHs	0.1823	0.1333	0.2916	0.0646	35.44
MMW PAHs	0.0820	0.0500	0.1100	0.0228	27.81
HMW PAHs	0.0546	0.0180	0.0853	0.0261	47.92
Σ8PAHs	0.3188	0.2328	0.487	0.0976	30.60

3.2 PAH contamination levels in the Teguere waters

According to the SEQ-Eau V2 guidelines, the eight quantified PAHs indicated very good to moderate water quality in both downstream and upstream areas (Table 6).

Table 6: Classification of Water Quality Based on PAH Concentrations Upstream and Downstream

PAH	Upstream concentration	Upstream classification	Downstream concentration	Downstream classification
Naphthalene	0.058	Very good	0.062	Very good
Acenaphthene	0.045	Very good	0.040	Very good
Fluorene	0.032	Good	0.028	Very good
Phenanthrene	0.068	Good	0.052	Good
Fluoranthene	0.044	Moderate	0.046	Moderate
Pyrene	0.034	Moderate	0.036	Moderate
Benzo(b)fluoranthene	0.024	Moderate	0.027	Moderate
Benzo(a)pyrene	0.006	Moderate	0.007	Moderate

Naphthalene and acenaphthene were classified as very good at both locations, while fluorene was classified as good downstream and very good upstream. Phenanthrene showed good-quality conditions in both areas. In contrast,

fluoranthene, pyrene, benzo(b)fluoranthene and benzo(a)pyrene were consistently classified as moderate quality in both downstream and upstream waters. The moderate classification was mainly driven by the very stringent SEQ-Eau V2 thresholds established for high-molecular-weight PAHs, particularly benzo(a)pyrene and benzo(b)fluoranthene.

3.3 Distribution of PAHs in Water According to the Number of Aromatic Rings

The distribution of individual PAHs within each molecular-weight class, defined according to the number of aromatic rings, revealed a clear predominance of specific compounds in both upstream and downstream waters (Figure 2). PAHs containing 2-3 aromatic rings were the most abundant, whereas those containing 5-6 aromatic rings were the least represented during the study period (Table 7). According to [42], the predominance of 2-3-ring PAHs in aquatic environments is mainly associated with biomass combustion. This observation is consistent with the conditions prevailing in the study area, where agricultural biomass burning is commonly practiced along the riverbanks. Furthermore, [42] and [43] reported that the relatively low proportion of high-molecular-weight PAHs (HMW-PAHs) in water can be attributed to their strong affinity for suspended particulate matter, particularly those originating from vehicular emissions. Among the 2-ring PAHs, naphthalene was the dominant compound, accounting for 42.87% and 47.59% of the total 2-ring PAHs in upstream and downstream waters, respectively. It was followed by acenaphthene and fluorene.

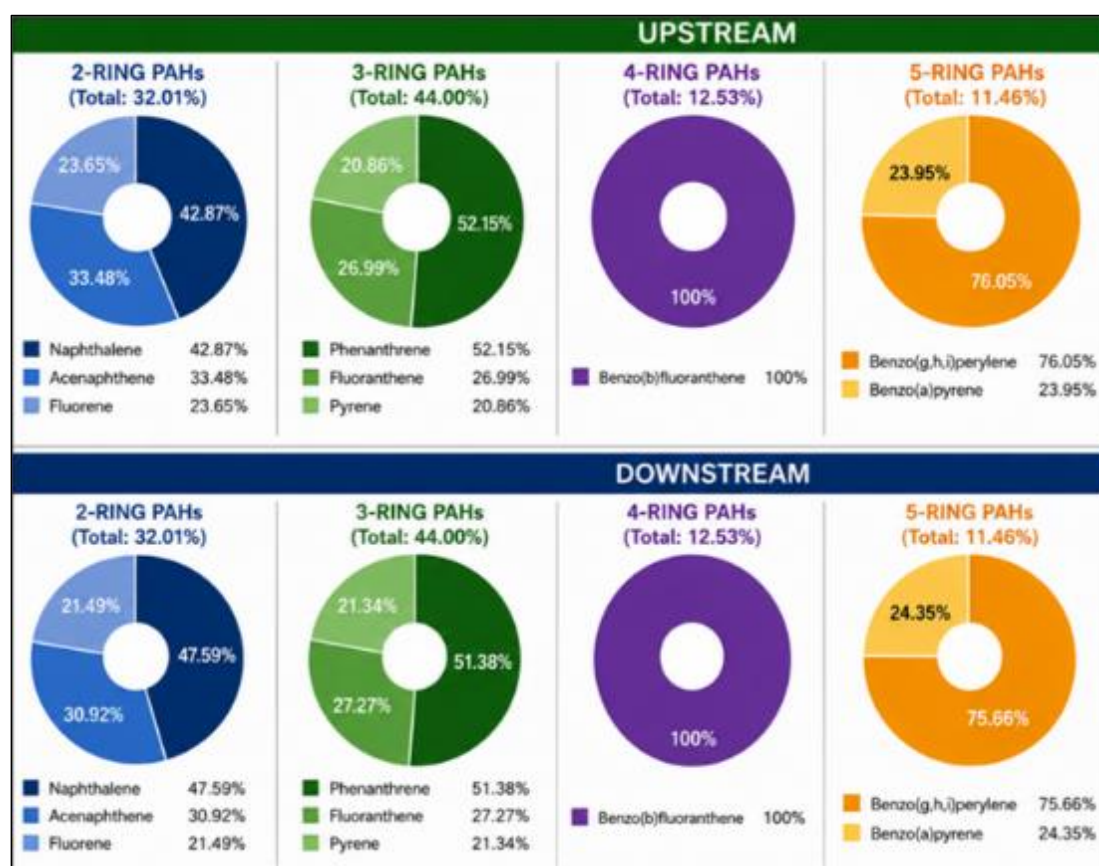


Figure 2: Mean Proportions of PAHs According to the Number of Benzene Rings in the Tégouéré River During the Study Period

Within the 3-ring PAH group, phenanthrene was the predominant compound upstream, representing 52.15% of the total concentration, and remained the most abundant compound downstream, accounting for 51.38%. Fluoranthene and pyrene also contributed substantially to this molecular-weight class. The 4-ring PAH fraction was entirely represented by benzo(b)fluoranthene, which accounted for 100% of the quantified 4-ring PAHs in both upstream and downstream waters. Among the 5-ring PAHs, benzo(g,h,i)perylene was the predominant compound, representing 76.05% and 75.66% of the total 5-ring PAHs in upstream and downstream waters, respectively. In contrast, benzo(a)pyrene contributed approximately 24% of this fraction. Overall, the very similar distribution patterns observed between upstream and downstream waters suggest a relatively homogeneous PAH composition throughout the study area. This consistency indicates the influence of common emission sources and/or effective mixing processes within the river system.

Table 7: Mean Proportions of PAHs According to the Number of Benzene Rings Upstream and Downstream During the Study Period.

Molecular Weight Class	Upstream (%)	Downstream (%)
Low-molecular-weight PAHs (LMW-PAHs, 2–3 rings)	66.00	62.56
Medium-molecular-weight PAHs (MMW-PAHs, 4 rings)	25.32	28.14
High-molecular-weight PAHs (HMW-PAHs, 5–6 rings)	8.68	9.30
Total	100.00	100.00

3.4 Origins of PAHs in the waters from this lacustrine system

The molecular diagnostics of PAHs were assessed in Table 8 to assess the ratio of individual PAHs components in relation to source or origin identification of PAHs [35]. The ratios assessed were used to distinguish petrogenic (unburnt crude oil, gas and coal), pyrogenic combustion of carbonaceous components (natural and anthropogenic) and phytogenic (plants, animal and microbial decomposition). The Flt/(Pyr + Flt) ratio showed mean values of 0.569 upstream and 0.566 downstream. Both values were above 0.50, suggesting a predominantly pyrogenic contribution associated with combustion processes. Similarly, the Flt/Pyr ratios were 1.323 upstream and 1.307 downstream, with values greater than 1 supporting a combustion-related or pyrogenic contribution to the observed PAH contamination. In contrast, the LMW/HMW ratios were relatively high, with mean values of 4.677 upstream and 4.262 downstream. The predominance of low-molecular-weight PAHs over high-molecular-weight PAHs is generally consistent with a significant petrogenic contribution and low-temperature combustion processes[2]. Overall, the diagnostic ratios suggest that PAHs in both upstream and downstream waters originate from mixed petrogenic and pyrogenic sources. This finding was also observed by [44] in the delta mangrove ecosystem (Niger), [45] in rice field soils of northwestern Peru, and [46] in Amazon Mangrove and Oyster Farming Areas (Brazil). The relatively similar ratios observed upstream and downstream further suggest that the PAH source pattern was broadly consistent throughout the study area rather than being associated exclusively with upstream inputs.

Table 8 : PAH Diagnostic Ratios and Source Interpretation

Diagnostic ratio	Upstream	Downstream	Typical interpretation
Flt/(Pyr + Flt)	0.569	0.566	Pyrogenic/combustion
Flt/Pyr	1.323	1.307	Pyrogenic/combustion
LMW/HMW	4.677	4.262	Petrogenic/low-MW predominance

3.5 Health risk assessment of PAHs

The level of risk (non-carcinogenic and carcinogenic) posed to people who are exposed to the organic micro pollutants present in the river Teguere by dermal contact was evaluated (Table 8). The HQs and ILCRs due to exposure of humans to PAHs in the bay were estimated from ADD.

3.5.1 Non-cancer risk assessment

Among adults, benzo(b)fluoranthene (BbF) exhibited the highest HQi values, with 1.23×10^{-4} upstream and 1.12×10^{-4} downstream, followed by pyrene, with 5.33×10^{-5} upstream and 5.63×10^{-5} downstream. Fluoranthene also presented relatively higher HQi values compared to other low-molecular-weight PAHs, while fluorene showed the lowest HQi values, with 1.45×10^{-5} upstream and 1.55×10^{-5} downstream. Phenanthrene was excluded from the assessment due to the unavailability of its dermal reference dose (RfD_{derm}). For children, HQi values were consistently higher than those for adults, with the highest values again observed for benzo(b)fluoranthene (3.61×10^{-4} upstream and 3.31×10^{-4} downstream), followed by pyrene (1.57×10^{-4} upstream and 1.69×10^{-4} downstream). Fluoranthene also contributed relatively elevated HQi values, whereas fluorene remained among the compounds with the lowest contribution to overall non-carcinogenic risk. The higher HQi values in children are attributable to exposure characteristics, particularly lower body weight relative to adults. The calculated hazard index (HI), representing the sum of HQi values for PAHs with available dermal $RfDs$, was 2.84×10^{-4} upstream and 3.00×10^{-4} downstream for adults. For children, HI values were 8.38×10^{-4} upstream and 8.85×10^{-4} downstream. All HI values were substantially below the benchmark of 1, indicating that combined exposure to quantified PAHs through dermal contact does not pose an appreciable non-carcinogenic health risk under the study assumptions. Comparison of the two sampling zones revealed that downstream areas exhibited slightly higher HI values than upstream areas for both adults and children. The slightly

higher HI values recorded downstream may reflect additional PAH inputs along the river course from anthropogenic activities. Similar downstream increases have been reported in other river systems [47], [48] and [49]. Overall, benzo(b)fluoranthene was the primary contributor to non-carcinogenic dermal risk, followed by pyrene and fluoranthene.

3.5.2 Carcinogenic Risk Assessment

The dermal carcinogenic risk assessment indicated that exposure to the quantified PAHs may pose a long-term carcinogenic concern at both sampling locations. The total cancer risk was estimated at 3.66×10^{-3} for adults and 2.16×10^{-3} for children upstream, whereas downstream values were 3.91×10^{-3} for adults and 2.31×10^{-3} for children. These values exceed the commonly accepted cancer-risk range of 10^{-6} to 10^{-4} , suggesting an increased potential for carcinogenic effects following prolonged dermal exposure to PAH-contaminated water. Among the evaluated compounds, benzo(a)pyrene and benzo(b)fluoranthene were the primary contributors to the overall carcinogenic risk at both locations. The relatively high risks associated with these high-molecular-weight PAHs are consistent with their recognized carcinogenic potential. The results also indicate that the carcinogenic risk was slightly higher downstream than upstream for both adults and children, although the difference between the two locations was relatively small. Comparable findings have been reported in previous studies examining polycyclic aromatic hydrocarbons (PAHs) in surface waters [47], [48] et [49]. Children presented a substantial dermal cancer risk under the exposure assumptions used in this assessment, highlighting their potential vulnerability to prolonged contact with contaminated surface water. Overall, the findings emphasize the need for continued monitoring of PAH contamination and for limiting prolonged dermal contact with the affected river water, particularly under conditions of repeated or long-term exposure.

Table 9: Hazard Quotients (HQ_i) of PAHs via Dermal Exposure in Adults and Children

PAHs components		HQi Adult		HQi Child	
	RfDderm	Upstream	Downstream	Upstream	Downstream
Naphtalène	0,02	$2,00 \times 10^{-5}$	$2,18 \times 10^{-5}$	$6,00 \times 10^{-5}$	$6,53 \times 10^{-5}$
Acénaphène	0,02	$3,06 \times 10^{-5}$	$2,78 \times 10^{-5}$	$9,20 \times 10^{-5}$	$8,34 \times 10^{-5}$
Fluorène	0,04	$1,45 \times 10^{-5}$	$1,55 \times 10^{-5}$	$4,34 \times 10^{-5}$	$4,65 \times 10^{-5}$
Phénanthrène	N/A	N/A	N/A	N/A	N/A
Fluoranthène	0,04	$4,00 \times 10^{-5}$	$4,22 \times 10^{-5}$	$1,19 \times 10^{-4}$	$1,27 \times 10^{-4}$
Pyrène	0,03	$5,33 \times 10^{-5}$	$5,63 \times 10^{-5}$	$1,57 \times 10^{-4}$	$1,69 \times 10^{-4}$
Benzo(b)fluoranthène	0,03	$1,23 \times 10^{-4}$	$1,12 \times 10^{-4}$	$3,61 \times 10^{-4}$	$3,31 \times 10^{-4}$
Benzo(a)pyrène	0,03	$2,60 \times 10^{-5}$	$2,70 \times 10^{-5}$	$7,70 \times 10^{-5}$	$8,10 \times 10^{-5}$
HI		$2,84 \times 10^{-4}$	$3,00 \times 10^{-4}$	$8,38 \times 10^{-4}$	$8,85 \times 10^{-4}$
PAHs components		ILCRderm Adult		ILCRderm Child	
	CSF (mg/kg/j) ⁻¹	Upstream	Downstream	Upstream	Downstream
Naphtalène	0,0073	1.28E-06	1.36E-06	7.55E-07	8.07E-07
Acénaphène	0,0073	1.96E-06	1.74E-06	1.15E-06	1.03E-06
Fluorène	0,0073	1.82E-06	1.59E-06	1.07E-06	9.40E-07
Phénanthrène	NA	NA	NA	NA	NA
Fluoranthène	0,0073	5.06E-06	5.29E-06	2.99E-06	3.12E-06
Pyrène	0,073	5.00E-05	5.29E-05	2.95E-05	3.12E-05
Benzo(b)fluoranthène	0,73	1.15E-03	1.32E-03	6.78E-04	7.76E-04
Benzo(a)pyrène	7,3	2.45E-03	2.53E-03	1.45E-03	1.49E-03
RI		3.66E-03	3.91E-03	2.16E-03	2.31E-03

3.6 Toxic and mutagenic equivalent Quotient of PAHs in surface water

The toxic equivalent quotients (TEQs) calculated for the water samples are presented in Table 10. The total TEQ was 0.009904 µg/L upstream and 0.010123 µg/L downstream. Benzo[a]pyrene was the predominant contributor to the total TEQ, accounting for 64.62% upstream and 65.20% downstream. Benzo[b]fluoranthene was the second major contributor, representing 32.30% downstream and 32.01% upstream. Consequently, BaP and BbF together accounted for approximately 96.92% of the total TEQ upstream and 97.21% downstream. The cumulative TEQ of PAHs in the Teguere River indicates that benzo[a]pyrene and benzo[b]fluoranthene will contribute to several health issues, such as neurobehavioral impairment, respiratory issues, birth deformities, reproductive impotence, dermatological issues, and many others in the human body [50, 51 and 52], as other PAHs did not make any substantial contribution. The predominance of BaP and BbF is mainly explained by their substantially higher TEFs compared with the lower-molecular-weight PAHs. Although some of the latter compounds occurred at concentrations comparable to or higher than BaP, their much lower TEF values (0.001) resulted in relatively small contributions to the overall BaP-equivalent toxicity. The mutagenic equivalent quotient (MEQ) was calculated to assess the overall mutagenic potential of the quantified PAH mixture, using benzo[a]pyrene as the reference compound (Table 11). The total MEQ measured 0.013895 µg/L upstream and 0.015176 µg/L downstream, indicating a marginally greater mutagenic potency of the PAH mixture downstream. The MEQ was primarily influenced by benzo(b)fluoranthene (BbF) and benzo(a)pyrene (BaP). Upstream, BbF contributed 53.94% and BaP 46.06% to the total MEQ, while downstream, BbF accounted for 56.51% and BaP for 43.49%. The greater contribution of BbF was attributed to its higher mean concentration, despite its lower MEF (0.25) compared to BaP (MEF = 1.0). The predominance of BbF and BaP suggests that the potential mutagenic activity of the PAH mixture is primarily associated with high-molecular-weight PAHs [53]. Overall, the downstream water exhibited a slightly higher mutagenic equivalent burden than the upstream water (0.015176 versus 0.013895 µg/L). The contributions of individual PAHs to the toxic equivalent quotient (TEQ) and MEQ may trigger both carcinogenic and non-carcinogenic health effects [35].

Table 10 : Toxic Equivalent Quotient (TEQ) of PAHs in Surface Waters Upstream and Downstream

		Upstream		Downstream	
HAP	TEF	TEQ (µg/L)	Contribution (%)	HAP-TEQ (µg/L)	Contribution (%)
Naphthalene	0.001	0.000058	0.59	0.000062	0.61
Acenaphthene	0.001	0.000045	0.46	0.000040	0.40
Fluorene	0.001	0.000032	0.32	0.000028	0.28
Phenanthrene	0.001	0.000092	0.93	0.000070	0.69
Fluoranthene	0.001	0.000044	0.44	0.000046	0.45
Pyrene	0.001	0.000034	0.34	0.000036	0.36
Benzo(b)fluoranthene	0.100	0.003198	32.30	0.003241	32.01
Benzo(a)pyrene	1.000	0.006400	64.62	0.006600	65.20
ΣTEQ	—	0.009904	100.00	0.010123	100.00

Table 11: Mutagenic Equivalent Quotient (MEQ) of PAHs in Surface Waters at Upstream and Downstream Sites

		Upstream		Downstream	
PAH	MEF	MEQ (µg/L)	Contribution (%)	MEQ (µg/L)	Contribution (%)
Benzo(b)fluoranthene	0.25	0.007495	53.94	0.008576	56.51
Benzo(a)pyrene	1.00	0.006400	46.06	0.006600	43.49
Σ MEQ	—	0.013895	100.00	0.015176	100.00

4 CONCLUSION

This study identified the presence of polycyclic aromatic hydrocarbons (PAHs) in surface waters of the Teguere River in Korhogo, northern Côte d'Ivoire, and provided an integrated assessment of contamination levels, probable sources, and potential human health implications. Eight of the 16 US-EPA priority PAHs were quantified, with mean $\Sigma 8$ PAH concentrations of 0.3320 $\mu\text{g/L}$ upstream and 0.3188 $\mu\text{g/L}$ downstream. Low-molecular-weight PAHs constituted the major fraction of the measured contamination. However, the detection of high-molecular-weight PAHs, particularly benzo[a]pyrene and benzo(b)fluoranthene, raises significant toxicological concerns. The SEQ-Eau V2 assessment indicated very good to moderate PAH-related water quality at both sampling locations, with no significant deterioration downstream. Diagnostic ratios indicated that PAHs originated from both petrogenic and pyrogenic sources, reflecting the influence of petroleum-related inputs and combustion processes. Similar PAH profiles and diagnostic ratios upstream and downstream suggest that contamination is associated with diffuse or continuous sources distributed along the river, rather than a single localized source. Human health risk assessment revealed dermal hazard indices well below the threshold value of 1 for both adults and children, indicating no appreciable non-carcinogenic risk under the exposure conditions considered. However, estimated total dermal cancer risks exceeded the acceptable range of 10^{-6} to 10^{-4} , reaching 3.66×10^{-3} and 3.91×10^{-3} for adults upstream and downstream, respectively, and 2.16×10^{-3} and 2.31×10^{-3} for children. Benzo[a]pyrene and benzo(b)fluoranthene were the principal contributors to carcinogenic risk. TEQ values of 0.009904 $\mu\text{g/L}$ upstream and 0.010123 $\mu\text{g/L}$ downstream, together with MEQ values of 0.013895 and 0.015176 $\mu\text{g/L}$, respectively, confirm the importance of high-molecular-weight PAHs in the overall toxic and mutagenic potential of the water. Benzo[a]pyrene was the predominant contributor to TEQ, while benzo(b)fluoranthene contributed most to MEQ. Although PAH concentrations did not indicate severe deterioration of water quality according to the SEQ-Eau V2 classification, the carcinogenic risk associated with prolonged dermal exposure warrants attention. Regular monitoring of PAHs is recommended along the Teguere River, particularly in areas subject to intense anthropogenic activities. Measures to reduce petroleum-related and combustion-derived inputs should be prioritized. Special consideration should be given to children, who may be more vulnerable due to their exposure characteristics. Further investigations involving seasonal sampling, additional sampling stations, and complementary exposure pathways such as ingestion and dietary exposure are necessary to provide a more comprehensive assessment of the environmental and public health risks associated with PAH contamination in the Teguere River.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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