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Occurrence, Spatial Distribution, and Ecological Risk of Phthalate Esters in Surface Sediments of West Lake, Hanoi, Vietnam

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Abstract

The study evaluates the occurrence, spatial distribution, temporal changes, and ecological risk of six phthalate esters (PAEs) – DMP, DEP, DBP, BBP, DEHP and DnOP – in surface sediments (0–5 cm) of West Lake, the largest urban lake in Hanoi, Vietnam. Sediment samples were collected at 10 stations during four campaigns: May 2022 and May 2023 (end of the dry season) and November 2022 and November 2023 (end of the rainy season). DBP, BBP and DEHP were detected in all 40 samples and DnOP in 29 samples (all below the limit of quantification, LOQ, of 3 µg/kg dw), whereas DMP and DEP were not detected (less than limit of detection, LOD, of 1 µg/kg dw). Procedural blanks were below the LOD, matrix-spike recoveries ranged from 83.0% to 97.0%, and the relative percent difference of duplicate analyses ranged from 0.7% to 6.9%. Σ_6PAEs (sum of the six PAEs) ranged from 18.50 to 46.53 µg/kg dry weight (dw), with campaign means of 33.83–34.49 µg/kg dw (n equal 10 stations per campaign). DEHP, DBP and BBP contributed approximately 55.2%, 20.8% and 19.9% of Σ_6PAEs, respectively, consistent with inputs from domestic wastewater and plastic materials in the densely urbanized areas surrounding the lake. Campaign means changed by −0.63 to +0.66 µg/kg dw (≤ 2.0%) between consecutive campaigns and showed neither a seasonal pattern nor an inter-annual trend; because no field replicates were collected, this apparent temporal stability should be interpreted with caution. Single-compound risk quotients (RQ) indicated minimal risk for BBP and DnOP, low risk for DBP and medium risk for DEHP, with all RQ values below the high-risk threshold (RQ ≥ 1).

Keywords: Ecological risk, phthalate esters (PAEs), sediment, urban lake, West Lake.

1. Introduction

Phthalate esters (PAEs) are a group of synthetic organic compounds widely used as plasticizers in the production of polyvinyl chloride (PVC), construction materials, food packaging, cosmetics, medical devices, and numerous other consumer products. Since PAEs do not form chemical bonds with the polymer matrix but exist only through physical interactions, they are readily released into the surrounding environment throughout the product lifecycle, from manufacturing and distribution to disposal [1–3]. Six PAEs have been listed as priority pollutants by the United States Environmental Protection Agency (USEPA), namely dimethyl phthalate (DMP), diethyl phthalate (DEP), di-n-butyl phthalate (DBP), butyl benzyl phthalate (BBP), bis(2-ethylhexyl) phthalate (DEHP), and di-n-octyl phthalate (DnOP), owing to their potential to cause endocrine disruption and adverse effects on the reproductive, developmental, and neurological functions of living organisms [4, 5].

Once released, PAEs tend to adsorb onto organic matter and suspended particles, subsequently settling and accumulating in bottom sediments over extended periods. As a result, sediments serve not only as a long-term sink for these contaminants but may also act as a secondary source of pollution through remobilization processes, exerting prolonged adverse effects on aquatic ecosystems [6–8].

Numerous studies worldwide have reported the presence of PAEs in sediments at concentrations ranging from tens of µg/kg to tens of thousands of µg/kg, depending on the degree of urbanization and industrial activity. In the Pearl River Delta, the total concentration of 16 PAEs (Σ_{16}PAEs) in sediments ranged from 567 to 47,300 µg/kg dry weight, with the highest values recorded in heavily industrialized areas [9]. In Kaohsiung Harbor (Taiwan), the mean total PAE concentration (including diisononyl phthalate, DiNP, which is not among the six target compounds of this study) reached 8,713 µg/kg dry weight, with DEHP and DiNP being the two predominant compounds [2]. In Taihu Lake (China), the total concentration of six PAEs (Σ_6PAEs) in lake surface sediments ranged from 1,120 to 18,710 µg/kg dry weight, with a marked increasing trend observed since the 1990s [10].

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Ecological risk assessment studies have also indicated that DEHP, DBP, and diisobutyl phthalate (DiBP) are the compounds posing the most significant risk to benthic organisms and aquatic ecosystems [3, 4, 11]. In terms of toxicity, PAEs are classified as endocrine disrupting compounds (EDCs), capable of exerting adverse effects on the reproductive, developmental, and neurological systems of both aquatic organisms and humans. DEHP has been classified by the International Agency for Research on Cancer (IARC) as a Group 2B substance-possibly carcinogenic to humans. Although numerous studies have been conducted worldwide on the distribution and ecological risk of PAEs in sediments, data on these compounds in inland water bodies of Vietnam remain limited, particularly for urban lake ecosystems subject to significant pressures from domestic wastewater, tourism, and urban development. Therefore, determining the concentrations, distribution characteristics, and ecological risk of PAEs in sediments is essential to provide a scientific basis for environmental quality management and the protection of aquatic ecosystems.

West Lake (Hanoi), covering an area of approximately 526 ha, is the largest urban lake in the city, playing a vital role in microclimate regulation, biodiversity conservation, and ecotourism development. However, to date, no study has systematically assessed the concentrations, temporal variation, and ecological risk of PAEs in the sediments of West Lake.

Addressing this research gap, the objectives of this study are: (1) to determine the concentrations and composition of PAEs in surface sediments of West Lake across spatial and temporal dimensions; (2) to compare PAE concentrations among four sampling campaigns in 2022–2023; and (3) to assess the ecological risk of PAEs to the aquatic ecosystem of West Lake. The findings are expected to provide a practical scientific basis for environmental monitoring, quality management, and the protection of urban lake ecosystems in Hanoi.

2. Materials and Methods

2.1. Study Area and Sampling

West Lake is the largest natural freshwater lake in Hanoi, located in Tay Ho Ward, Hanoi (21°03'N, 105°49'E). The lake has a perimeter of approximately 17 km, a surface area of about 526 ha, and an average depth of 2–3 m. The surrounding area is characterized by high-density urban residential zones, tourist areas, hotels, and restaurants.

Ten sediment sampling stations (S1–S10) were distributed around the lake (Fig. 1), representing diverse environments, including areas directly receiving wastewater discharge, recreational and tourism zones, areas remote from pollution sources, and the central basin of the lake. Station locations are shown in Fig. 1. Surface sediment samples (0–5 cm depth) were collected during four campaigns: May 2022 and May 2023 (end of the dry season) and November 2022 and November 2023 (end of the rainy season), giving a total of 40 samples (10 stations × 4 campaigns). All samples were collected with the same grab sampler; at each station and campaign, one sample was obtained from a single grab (i.e. samples were not composited). All samples were preserved at 4 °C and transported to the laboratory within 24 hours of collection.

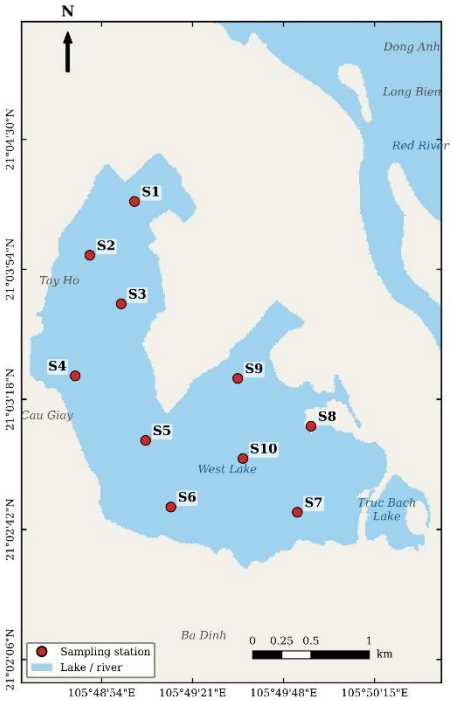


Fig. 1. Location of the ten sediment sampling stations (S1–S10) in West Lake, Hanoi, Vietnam

2.2. Sample Treatment and Analysis

Sediment samples were freeze-dried at −50 °C, ground, sieved through a 0.25 mm mesh and stored at −20 °C until analysis. PAEs were extracted by ultrasonication with a dichloromethane/acetone mixture (1:1, v/v), in line with the general principles of USEPA Method 3550C for ultrasonic extraction. The extracts were purified by silica gel column chromatography and concentrated using a rotary vacuum evaporator.

The six target PAEs (DMP, DEP, DBP, BBP, DEHP and DnOP; Section 1) were analysed by gas chromatography–mass spectrometry (GC-MS; Agilent 7890B/5977A) with an HP-5MS capillary column (30 m × 0.25 mm × 0.25 µm), following the laboratory's standard operating procedure (SOP); the instruments were calibrated and maintained regularly.

In each campaign, for quality assurance and quality control (QA/QC), one procedural blank, one duplicate sample, and one matrix-spiked sample were analysed together with the ten field samples; the sample from station S10 was used for the duplicate and matrix-spike

analyses. Each analytical batch therefore comprised 13 analyses (ten field samples and three QC samples), i.e. QC samples accounted for 3 of the 13 analyses (23%) in each campaign. The method limit of detection (LOD) and limit of quantification (LOQ), as specified for the laboratory's validated method, were 1 µg/kg dry weight (dw) and 3 µg/kg dw, respectively, for each of the six PAEs. Since PAEs, particularly DEHP and DBP, are common laboratory contaminants, procedural blanks were processed and analysed with each batch; all six PAEs were below the LOD in the blanks of all four campaigns, so no blank correction was required.

For the matrix spike, a portion of the S10 sample was fortified with each PAE at a level equivalent to 10 µg/kg dw and analysed in the same way as the field samples. Recovery (H, %) was calculated using (1):

$$H = \frac{C_{\text{spiked}} - C_{\text{sample}}}{C_{\text{added}}} \times 100 \quad (1)$$

where C_{spiked} and C_{sample} are the concentrations measured in the spiked and unspiked sample and C_{added} is the added concentration. Recoveries ranged from 83.0% to 97.0% for the six PAEs (Table 1), and concentrations were not corrected for recovery. The relative percent difference (RPD) between duplicate analyses, calculated as the absolute difference divided by the mean of the two results, ranged from 0.7% to 6.9% for the detected compounds. Since the duplicate was a laboratory duplicate of the homogenised S10 sample, the RPD reflects analytical repeatability only; no field replicates were collected. Concentrations below the LOD were reported as not detected (ND) and set to zero when calculating Σ₆PAEs (the sum of the six target PAEs); DnOP concentrations between the LOD and the LOQ were retained as estimated values.

Table 1. Quality assurance and quality control results for the six phthalate esters in West Lake sediments (2022–2023)

PAE	LOD	LOQ	Blank	Recovery (%)	RPD (%)
DMP	1	3	< LOD	91.0–92.0	–
DEP	1	3	< LOD	89.0–96.0	–
DBP	1	3	< LOD	91.4–95.0	1.18–2.44
BBP	1	3	< LOD	89.3–94.4	0.74–2.81
DEHP	1	3	< LOD	83.0–92.6	1.19–3.73
DnOP	1	3	< LOD	89.9–97.0	1.41–6.90

LOD, LOQ and blank values in µg/kg dw. Blank: procedural blanks, one per campaign (n = 4). Recovery: matrix spike of S10 at 10 µg/kg dw, one per campaign (n = 4). RPD: duplicate analysis of S10, one per campaign (n = 4); – : not calculated because the compound was not detected. Campaign-specific QA/QC results are available from the corresponding author upon request.

2.3. Ecological Risk Assessment

The ecological risk of PAEs in sediments was assessed using the Risk Quotient (*RQ*) approach, calculated according to the following formula:

$$RQ = MEC / PNEC \quad (2)$$

where *MEC* (measured environmental concentration) is the concentration of each *PAE* measured in sediment (µg/kg dw) and *PNEC* (predicted no-effect concentration) is the sediment *PNEC* for benthic organisms reported from Gao *et al*. [3]. Since all PNEC values were taken from a single source, the resulting risk classification depends on these values and should be interpreted with caution. Risk levels were classified according to a commonly applied four-tier scheme: $RQ < 0.01$, minimal risk; $0.01 \leq RQ < 0.1$, low risk; $0.1 \leq RQ < 1$, medium risk; and $RQ \geq 1$, high risk. In addition, since the total organic carbon (TOC) content of the sediments was not measured, the *RQ* values could not be normalised to sediment organic carbon.

2.4. Statistical Analysis

Descriptive statistics (mean, sample standard deviation (SD) calculated with $n - 1$, minimum and maximum) were calculated for each sampling campaign ($n = 10$ stations) using Microsoft Excel, with *ND* values set to zero. No formal statistical test was applied to the differences between campaigns, which are therefore reported descriptively; within-station differences between campaigns are discussed in Section 3.3 in relation to analytical and field-sampling variability.

3. Results and Discussion

3.1. Concentrations and Composition of Phthalate Esters in West Lake Sediments

DBP, BBP, and DEHP were detected in all 40 samples. DnOP was detected in 29 of the 40 samples (7–8 stations per campaign), always at concentrations between the LOD and the LOQ (1.02–2.96 µg/kg dw), whereas DMP and DEP were not detected in any sample (< 1 µg/kg dw). The total concentration of Σ₆PAEs ranged from 18.50 to 46.53 µg/kg dw, with campaign means ranging from 33.83 ± 9.39 to 34.49 ± 9.47 µg/kg dw ($n = 10$ stations per campaign). Table 2 summarizes the mean concentrations and standard deviations (Mean ± SD) of each individual compound across the four sampling campaigns.

Among the six compounds analyzed, DEHP was the dominant compound, with mean concentrations ranging from 18.68 ± 4.61 µg/kg dw (May 2022) to 19.05 ± 4.64 µg/kg dw (November 2022), contributing approximately 55.2% of total Σ₆PAEs. DBP ranked second with a mean contribution of 20.8%, followed by BBP at approximately 19.9%. DnOP accounted for only 4.2% of total Σ₆PAEs, and DMP and DEP were not detected.

Table 2. Mean concentrations (± SD, µg/kg dw) of phthalate esters in West Lake surface sediments

PAE	May 2022 (Mean ± SD)	Nov 2022 (Mean ± SD)	May 2023 (Mean ± SD)	Nov 2023 (Mean ± SD)	% of Σ_6PAEs
BBP	6.74 ± 1.85	6.77 ± 1.84	6.76 ± 1.89	6.81 ± 1.85	19.9%
DMP	ND	ND	ND	ND	–
DnOP[a]	1.39 ± 1.05	1.41 ± 1.06	1.50 ± 0.96	1.38 ± 1.05	4.2%
DBP	7.02 ± 2.09	7.26 ± 2.22	6.89 ± 2.02	7.19 ± 2.17	20.8%
DEP	ND	ND	ND	ND	–
DEHP	18.68 ± 4.61	19.05 ± 4.64	18.71 ± 4.57	18.88 ± 4.53	55.2%
Σ_6PAEs	33.83 ± 9.39	34.49 ± 9.47	33.86 ± 9.21	34.27 ± 9.38	100%

n = 10 stations per campaign. ND: not detected (< LOD, 1 µg/kg dw), set to zero. [a] Estimated values between the LOD and the LOQ (3 µg/kg dw); the DnOP and Σ_6PAEs statistics include these estimates.

Both DEHP (log K_{ow} 7–8) and DBP (log K_{ow} 4.45) are hydrophobic and partition preferentially into the particulate phase in aquatic environments [12]. Regarding their sources, DEHP and DBP are the most widely used plasticizers in the manufacture of PVC products, food packaging, toys, pipes, and construction materials - products consumed in large quantities in the densely urbanized areas surrounding West Lake. Untreated domestic wastewater and stormwater runoff from residential areas and commercial centers around the lake are considered the primary pathways through which these compounds enter the sediment system. This pattern is in agreement with findings from numerous urban lakes and rivers across Asia, where DEHP and DBP have likewise been identified as the two predominant compounds. In Taihu Lake (China), DEHP contributed more than 70% of total PAEs (ΣPAEs) in sediments [3]. However, in terms of absolute values, the Σ_6PAEs concentrations at West Lake (campaign means 33.83–34.49 µg/kg dw) were considerably lower than those reported in urban water bodies subject to heavy industrial loading, such as the Pearl River Delta (567–47,300 µg/kg dw), reflecting the characteristic profile of an urban lake primarily influenced by domestic wastewater and tourism-related activities.

In contrast, DMP and DEP were not detected in any sample (< 1 µg/kg dw), which is consistent with their relatively high water solubility (log K_{ow} of DMP = 1.61; DEP = 2.38 [12]), favouring their distribution in the aqueous phase rather than accumulation in sediments. DnOP was detected in 29 of the 40 samples at concentrations between the LOD and the LOQ (1.02–2.96 µg/kg dw), accounting for approximately 4.2% of total Σ_6PAEs; because these values are below the LOQ, they should be regarded as estimates. Its sediment PNEC (300 µg/kg dw) is higher than those of DEHP (140 µg/kg dw) and DBP (200 µg/kg dw), indicating lower toxicity toward benthic organisms. Overall, the PAE composition profile at West Lake reflects the characteristic signature of urban pollution sources, with DEHP and DBP as the dominant compounds, consistent with PAE contamination patterns reported in urban lakes and rivers across developing countries.

From a physicochemical perspective, the high log K_{ow} of DEHP strongly favours sorption onto sediment organic matter rather than retention in the dissolved phase, which is consistent with its dominant share of Σ_6PAEs at every station. In addition, long-chain congeners such as DEHP and DnOP are degraded more slowly than short-chain PAEs, since their bulky alkyl side chains hinder the enzymatic hydrolysis of the ester bonds (first to the monoester and then to phthalic acid). The combination of strong sorption and slow degradation may therefore explain why DEHP dominates the PAE profile of West Lake sediments. However, because the total organic carbon (TOC) content and grain-size distribution of the sediments were not determined in this study, this interpretation is based on the general behaviour of PAEs reported in the literature rather than on site-specific evidence, and should be regarded as tentative.

3.2. Spatial Distribution

Regarding spatial distribution (Fig. 1), station S9 consistently recorded the highest Σ_6PAEs concentrations across all sampling campaigns (44.30–46.53 µg/kg dw), while S1 consistently exhibited the lowest concentrations (18.50–19.61 µg/kg dw), followed by S8

(21.31–22.03 µg/kg dw). Stations S4 and S2 also recorded relatively elevated concentrations (43.15–44.04 and 40.62–42.18 µg/kg dw, respectively). This uneven spatial distribution can be attributed to differences in the degree of influence from surrounding pollution sources.

Stations S9, S4, and S2 (Fig. 1) are located in proximity to high-density residential areas and tourism service facilities, which may contribute to their comparatively higher PAE concentrations. However, discharge points were not mapped in this study, and S9 is located offshore in the eastern basin; this relationship should therefore be regarded as tentative. The lower concentrations at S1 and S8, however, cannot be explained simply by distance from anthropogenic activities, because S8 is located near the densely built-up eastern shore close to Truc Bach; local factors such as sediment grain size, organic matter content, and hydrodynamic conditions, which were not measured in this study, may also contribute. At every station, Σ_6PAEs varied by no more than 2.23 µg/kg dw across the four campaigns (within-station coefficient of variation, CV, 0.6–2.9%); consequently, the ranking of stations remained essentially unchanged (see Section 3.3). Since the proximity to pollution sources was assessed qualitatively, this interpretation should be verified by quantitative source analysis in future studies.

3.3. Temporal Variation

Table 3 summarizes the variation of Σ_6PAEs concentrations across the four campaigns (n = 10 stations per campaign; Fig. 2 shows the mean ± SD, minimum and maximum). Mean Σ_6PAEs was 33.83 µg/kg dw in May 2022, 34.49 µg/kg dw in November 2022, 33.86 µg/kg dw in May 2023, and 34.27 µg/kg dw in November 2023. Between consecutive campaigns, the mean increased by 0.66 µg/kg dw (+2.0%) from May to November 2022, decreased by 0.63 µg/kg dw (−1.8%) from November 2022 to May 2023, and increased by 0.41 µg/kg dw (+1.2%) from May to November 2023. At the station level, Σ_6PAEs differed little between campaigns (within-station CV 0.6–2.9%). This variability should be distinguished from the analytical repeatability indicated by the laboratory duplicates (RPD 0.7–6.9%; Table 1), which reflects only subsampling and measurement of a homogenised sample. Differences between independently collected grab samples may additionally reflect small-scale spatial heterogeneity, small changes in sampling position, differences in sediment characteristics and differences between analytical batches, and would therefore normally be expected to exceed the analytical repeatability. The low within-station variability observed here thus indicates an unusually high degree of consistency among campaigns. Since no field replicates were collected, field-sampling variability could not be quantified, and the apparent temporal stability should be interpreted with caution. Within these limits, the data do not indicate a seasonal pattern. Since no formal statistical test of temporal differences was performed, these differences are reported descriptively and are not interpreted as evidence of a temporal effect.

Table 3. Total concentrations of phthalate esters (Σ_6PAEs, µg/kg dw) in West Lake sediments by sampling campaign

Sampling period	Min Σ_6PAEs	Max Σ_6PAEs	Mean Σ_6PAEs	DEHP (% of Σ_6PAEs)
May 2022	18.50	45.20	33.83	~55%
Nov 2022	19.30	46.53	34.49	~55%
May 2023	18.55	44.30	33.86	~55%
Nov 2023	19.61	45.89	34.27	~55%

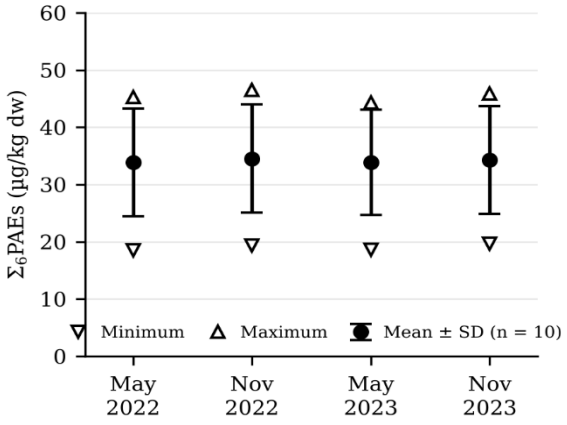


Fig. 2. Total phthalate ester concentrations (Σ_6PAEs) in West Lake surface sediments in the four sampling campaigns

Two considerations argue against interpreting these differences as a seasonal process. First, the rainy season in Hanoi extends from approximately May to October; the May samples therefore reflect conditions at the end of the dry season, whereas the November samples reflect conditions after the period of maximum stormwater input. Second, in a shallow lake the 0–5 cm surface layer is likely to integrate several years of deposition and is therefore unlikely to respond measurably to changes in water level or redox conditions over a six-month

interval. The four campaigns are therefore treated here as repeated measurements at the same stations rather than as evidence of seasonal dynamics.

Mean Σ₆PAEs concentrations were virtually identical in 2022 (34.16 µg/kg dw) and 2023 (34.06 µg/kg dw; difference −0.3%; Table 3), indicating no inter-annual change over the study period. Since this comparison is based on only two years of data, the apparent stability of PAE levels should be confirmed by longer-term monitoring; it is therefore not used as a basis for the risk interpretation or management recommendations in this study.

3.4 Comparison with Domestic and International Studies

Table 4 compares the Σ₆PAEs concentrations in West Lake sediments with those reported in comparable studies worldwide. PAE concentrations in West Lake sediments (18.50–46.53 µg/kg dw) were the lowest among the studies listed in Table 4, although the number of compounds summed differs among studies.

Table 4. Comparison of total phthalate ester concentrations (ΣPAEs) in sediments of West Lake and other water bodies

Study area	No. of PAEs summed	ΣPAEs range (µg/kg dw)	Reference
West Lake, Vietnam (This study)	6 PAEs	18.50 – 46.53	This study
Taihu Lake basin, China	6 PAEs	5,150 – 20,900	[3]
Jiulong River, China	6 PAEs	4 – 1,600	[4]
Lesser Himalayas lake, India	4 PAEs	6 – 357	[13]
Pearl River Delta, China	16 PAEs	567 – 47,300	[9]

Compared to studies conducted in Chinese lakes and rivers, PAE concentrations at West Lake were considerably lower (Taihu Lake basin: 5,150–20,900 µg/kg dw [3]; Pearl River Delta: 567–47,300 µg/kg dw [9]). The Taihu values reported for the wider lake basin [3] differ from those reported for Taihu Lake sediments alone (1,120–18,710 µg/kg dw [10]), reflecting differences in study area and sampling period. PAE concentrations at West Lake were within the range reported for a less urbanized freshwater lake in the Lesser Himalayas (Σ_4PAEs: 6–357 µg/kg dw [13]). Even at these relatively low levels, PAEs warrant continuous monitoring owing to their environmental persistence and potential for bioaccumulation.

Such inter-study comparisons should, however, be interpreted with caution. Differences in the sediment fraction analysed (below 0.25 mm in this study), in extraction methods and recoveries, and in the number of compounds summed (4 to 16 PAEs; Table 4) can by themselves produce substantial differences in reported concentrations, and are simpler explanations for part of the gap between West Lake and other water bodies than differences in pollution sources. Beyond these methodological factors, the lower concentrations at West Lake are consistent with a catchment dominated by domestic wastewater and tourism activities rather than industrial discharges. Continued monitoring with harmonised methods would allow a more robust comparison with other urban water bodies in the region.

3.5 Ecological Risk Assessment

The ecological risk of PAEs in West Lake sediments was assessed using the RQ approach. Table 5 presents the mean RQ values calculated for each individual compound across the four sampling campaigns, based on the PNEC values reported by Gao *et al.* [3], listed in the last row of Table 5. The risk level for each campaign corresponds to the highest compound-specific RQ (DEHP), classified according to the four-tier scheme described in Section 2.3; RQs were not calculated for DMP and DEP, which were not detected (ND).

Table 5. Risk quotients (RQ) of phthalate esters in West Lake sediments by sampling campaign

Sampling period	BBP	DMP	DnOP	DBP	DEP	DEHP	Risk level
May 2022	3.7×10^{-3}	ND	4.6×10^{-3}	3.5×10^{-2}	ND	1.3×10^{-1}	Medium
Nov 2022	3.8×10^{-3}	ND	4.7×10^{-3}	3.6×10^{-2}	ND	1.4×10^{-1}	Medium
May 2023	3.8×10^{-3}	ND	5.0×10^{-3}	3.4×10^{-2}	ND	1.3×10^{-1}	Medium
Nov 2023	3.8×10^{-3}	ND	4.6×10^{-3}	3.6×10^{-2}	ND	1.3×10^{-1}	Medium
PNEC (µg/kg dw) [3]	1.8×10^{3}	1.91×10^{4}	3.0×10^{2}	2.0×10^{2}	3.83×10^{4}	1.4×10^{2}	

DEHP exhibited the highest *RQ* values in all campaigns (0.13–0.14), owing to its relatively low sediment PNEC (140 µg/kg dw), and was classified as medium risk. DBP (*RQ* 0.034–0.036) was classified as low risk, whereas BBP (*RQ* ≈ 0.004) and DnOP (*RQ* ≈ 0.005) posed minimal risk; *RQ*s for DMP and DEP were not calculated because neither compound was detected. At the station level, the highest *RQ*s were 0.18 for DEHP and 0.049 for DBP (S9, November 2022), so the risk classification did not change. Even under a highly conservative assumption that the entire Σ_6PAEs concentration at the most contaminated station (S9; 46.53 µg/kg dw) consisted of DEHP, the resulting *RQ* (0.33) would remain below the high-risk threshold (*RQ* ≥ 1).

Overall, the ecological risk posed by PAEs in West Lake sediments is currently minimal to medium, with no compound exceeding the high-risk threshold. DEHP is the compound of greatest concern because it has the highest *RQ* values and is persistent in sediments; continued monitoring of DEHP in West Lake sediments is therefore recommended.

It should also be emphasized that the RQ approach applied in this study evaluates each PAE compound individually, based on the ratio of its measured concentration to its respective PNEC. This single-compound framework does not account for the possibility of additive or synergistic toxicity arising from the simultaneous presence of multiple PAEs – and indeed other co-occurring organic contaminants – within the same sediment matrix. Given that DEHP and DBP together account for roughly three-quarters of total Σ_6PAEs at every station, the cumulative risk to benthic organisms exposed concurrently to this compound mixture may be somewhat higher than that suggested by individual RQ values considered in isolation. Future assessments incorporating a hazard-index or mixture-toxicity approach, together with biological effect indicators such as benthic community structure or biomarker responses in resident organisms, would help refine the ecological risk characterization of West Lake sediments and provide a more conservative basis for management decisions.

4. Conclusion

This study provides a first baseline dataset on the occurrence, spatial distribution and ecological risk of six PAEs in surface sediments of West Lake, Hanoi, based on four sampling campaigns in 2022–2023. DBP, BBP, and DEHP were detected in all samples, DnOP in 29 of the 40 samples (below the LOQ), and DMP and DEP were not detected; Σ_6PAEs ranged from 18.50 to 46.53 µg/kg dw. DEHP, DBP, and BBP were the dominant compounds, contributing approximately 55.2%, 20.8%, and 19.9% of Σ_6PAEs, respectively, and the highest concentrations occurred at S9, S4, and S2, near densely populated and tourism areas. Differences among campaigns were small (≤ 2.0%) and indicated neither a seasonal pattern nor an inter-annual trend, although this apparent stability could not be evaluated against field-sampling variability. Single-compound RQs indicated minimal risk for BBP and DnOP, low risk for DBP, and medium risk for DEHP; DEHP therefore warrants priority in future monitoring because of its highest RQ values and persistence in sediments. The main limitations of this study are the lack of sediment physicochemical data (TOC and grain size), the collection of a single grab sample per station and campaign without field replicates, and the short monitoring period (two years). In addition, DnOP concentrations were below the LOQ and should be regarded as estimates, and the QA/QC programme comprised one procedural blank, one laboratory duplicate and one matrix spike per campaign, all at a single station (S10).

Acknowledgments

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Data Availability

The data supporting the findings of this study, including station-level concentrations of the six PAEs for all four sampling campaigns and the corresponding batch-level QA/QC results, are available from the corresponding author upon reasonable request for verification and research purposes.

Declaration

The authors declare no conflict of interest. The authors confirm that the data reported in this study are authentic and accurately represent the results obtained. The authors take full responsibility for the accuracy, reliability, and integrity of the data and the validity of the reported results.

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