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Metal Contamination of Surface Sediments in an Urban Wetland: The Case of the Urban Natural Reserve of Pikine Grand Niaye and Dependencies (UNRPGND), Senegal

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Abstract

This study assessed the concentrations of cadmium (Cd), lead (Pb), and mercury (Hg) in surface sediments from seven lakes within the Urban Natural Reserve of Pikine Grande Niaye and Dependencies, using atomic absorption spectrometry. Cd concentrations ranged from 6.17 to 8.34 mg/kg, showing relatively uniform levels across the lakes. In contrast, Pb exhibited greater variability, with concentrations between ranging from 0.76 to 4.18 mg/kg, while Hg concentrations ranged from 2.15 to 3.72 mg/kg. Although spatial variations in metal concentrations were observed, the Kruskal-Wallis test revealed no statistically significant differences among the lakes. Seasonal variations were more pronounced. Cd concentrations were significantly higher during the wet season compared to the dry season. Pb levels also peaked in the wet season, with the highest values recorded at Lac Kakhira. Hg concentrations remained low during the dry season but increased notably in the wet season, particularly at Lac Maristes 1. The Kruskal-Wallis test confirmed significant seasonal differences for both Cd and Pb, while Hg concentrations did not show significant seasonal variation but not for Hg. The contamination factor indicated high contamination levels by for Cd and Hg, especially at Lakes Lac Maristes 1 and Lac Maristes 2, whereas Pb contamination remained low across all sites. The geo-accumulation index confirmed significant contamination by Cd but not by Pb, suggesting that Pb currently poses a limited threat to the reserve's ecosystem. These findings underscore the urgent need for continuous environmental monitoring and the implementation of proactive management strategies to safeguard this vulnerable urban wetland.

Keywords

Water Quality, Urban Wetland, Heavy Metals, Protected Area, Environmental Quality Index and Sediment

1. Introduction

Urban wetlands are critical ecosystems that deliver a range of essential services, including water filtration, flood regulation, carbon sequestration, and the conservation of biodiversity [1]. However, their close proximity to expanding urban and industrial areas renders them highly vulnerable to various pollutants, particularly heavy metals such as cadmium (Cd), mercury (Hg), and lead (Pb). These metals, known for their persistence, accumulate in sediments over time and pose long-term environmental and public health risks [2] [3]. Unlike organic contaminants, heavy metals do not degrade naturally and can remain active in aquatic systems for decades, entering the food web through bioaccumulation and biomagnification processes.

The situation is particularly concerning in Dakar, Senegal, where rapid urbanization and industrialization have intensified environmental pressures. Although the Dakar region covers only about 0.3% of Senegal's total land area, it hosts more than a quarter of the national population and approximately 80% of its industrial activities [4]. Previous studies have reported significant levels of heavy metal contamination in the coastal and aquatic ecosystems surrounding Dakar [5]. Factors such as unregulated industrial waste disposal, untreated domestic sewage, agricultural runoff, and atmospheric deposition contribute substantially to this environmental burden [6] [7].

In densely populated urban districts like Pikine, where informal settlements and industrial zones coexist with limited waste management infrastructure, the risks associated with heavy metal contamination are magnified. Sediment contamination not only disrupts the ecological balance of wetlands but also threatens human health through the consumption of contaminated aquatic species. One particularly vulnerable species is *Sarotherodon melanotheron* (black-chinned tilapia), an important component of the local food web and a common source of protein for nearby communities [4] [8].

The Pikine Grande Niaye and Dependencies Urban Natural Reserve (UNRPGND) is one of the last surviving urban wetlands in Dakar. Originally established to protect the "Niayes"—coastal Niayes, coastal depressions characterized by freshwater wetlands—this, this reserve plays a vital role in ecological functions such as water purification, climate regulation, and providing critical habitat for migratory bird species [9]. Nevertheless, the reserve is increasingly threatened by anthropogenic activities, particularly the influx of untreated industrial effluents and domestic wastewater, which have led to significant sediment degradation [10].

In light of these challenges, the present study aims to comprehensively assess the environmental status of the UNRPGND through the evaluation of heavy metal contamination in its sediments. Using atomic absorption spectrometry (AAS), we will quantify metal concentrations, examine spatial and temporal variations in contamination levels, and apply multiple pollution indices to assess the degree of environmental degradation. The findings of this study are expected to inform conservation strategies and support the sustainable management of urban wetlands under increasing anthropogenic pressure.

2. Materials and Methods

2.1. Description of the Site and Sediment Sampling

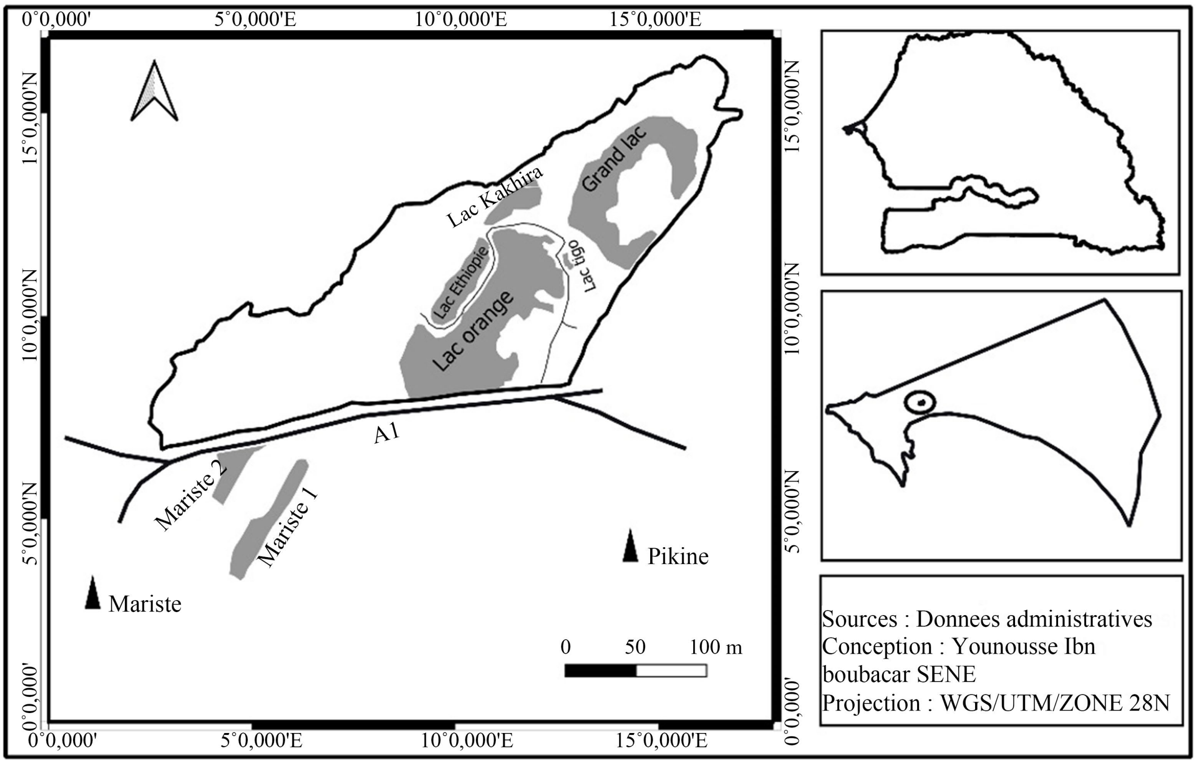

Figure 1. Map of the urban nature reserve.

The study site is the Urban Natural Reserve of Pikine Grande Niaye and Dependencies (UNRPGND), situated at located in the heart of the Dakar region, covering an area of 773.4 acres (**Figure 1**). This reserve includes the Pikine Niayes (Technopole site) and the Hann Maristes Niayes. It contains seven lakes, five within the Technopole and two in Maristes. As the largest area of green space in Dakar, this region plays a crucial role in bird conservation, offering shelter to 239 species. However, it has undergone significant changes, primarily due to urban expansion. The construction of various infrastructure projects directly within the wetland has led to its progressive degradation. Additionally, the study site is situated in a natural depression, making it a collection point for runoff from the surrounding areas during the wet season.

Sediment samples were collected from the seven lakes of the reserve during both the wet and dry seasons, between February 2021 and March 2022 (**Figure 1**), totalling totaling 28 surface sediment samples. Approximately 1 kg (0 - 5 cm depth) of wet sediments were sediment was collected at each sampling point. The samples were placed in plastic bags and stored in a cool box at 4˚C to preserve their integrity before being transported to the laboratory for analysis.

2.2. Chemical Analysis

For atomic absorption spectrometry (AAS110) calibration, analytical standards of Pb, Cd, and Hg were used. For each sample, 1.5 g was of sediment was mineralized using 15 mL of 65% nitric acid, 3 mL of hydrochloric acid, and 0.5 mL of perchloric acid in Pyrex volumetric flasks, along with 6 mL of 1% nitric acid. The digested solutions were diluted to 50 mL with acidified water (0.1 N), and metal concentrations were measured using graphite furnace AAS (AAS110) atomic absorption spectrometry (GFAAS). Mercury was quantified using cold vapor atomic absorption spectrometry (CV-AAS110). Calibration solutions were prepared for each metal, and fortified sample were samples were used to calculate recovery rates, with spike concentrations within the calibration range. All concentrations are expressed in mg/kg dry weight. The limit of quantification (LOQ) for Pb, Cd, and Hg of limits of quantification (LOQs) for Pb, Cd, and Hg were 0.05, 0.005, and 0.01 mg·kg^{-1}, respectively.

2.3. Quality Assurance and Quality Control

A strict QA/QC protocol was applied to ensure the accuracy and reliability of these metal analysis the metal analyses. A multi-element calibration was performed using single-element standard solutions (SCP Sciences Science). To ensure instrument stability and analytical precision, standard solutions were injected after every three samples during analysis.

2.4. Pollution Indices

Several methods exist for calculating the degree of sediment metal enrichment [11] [12]. Several authors have proposed approaches to assess contamination levels by relating numerical field results to a descriptive contamination scale ranging from low to high intensity Various authors have proposed methods to assess contamination levels by linking numerical field data to a descriptive scale of contamination intensity, ranging from low to high [13] [14].

These methods do not account for the speciation of heavy metals in sediments but instead indicate the contamination level within a specified area by trace metals (TMs) and polycyclic aromatic hydrocarbons (PAHs) on the basis of based on their total concentrations. The three methods used in this study are discussed in the sections below.

The indices (**Table 1**) were calculated using reference concentrations from the Earth's crust, as proposed by Wedepohl [15]. The factors were determined across all four sampling campaigns.

Table 1. Concentrations of heavy metals studied in the earth crust (Adopted from Wedepohl,1995).

Variables	Cd	Pb	Hg
Upper Continental Crust ($mg\cdot kg^{-1}$)	0.102	17	0.056

2.5. Contamination Factors

The contamination factor (C_f) is used to assess the pollution status of individual metals within a specified area, with Csample and Cbackground representing the extractable concentrations of metals in surface and background sediments, respectively. Cf is commonly used to assess the potential ecological hazard of pollutants in sediments [16]-[18]. **Table 2** shows the different classes of contamination factor.

$$C_f = \frac{C_{sample}}{C_{background}}$$

Table 2. Contamination factor class.

Class	Value	Pollution intensity
1	$CF \leq 1.5$	Absent to low
2	$1.5 < CF \leq 3$	Moderate
3	$3 \leq CF \leq 6$	Considerable
4	$6 \leq CF$	Very strong

2.6. Modified Contamination Degree

A study by Hakanson [13] suggests that the numerical sum of all contamination factors for the selected elements represents the total contamination factor (CF) for a specific sediment. However, Hakanson's method was originally designed for polychlorinated biphenyls (PCBs), requiring the analysis of eight specific species to accurately determine the degree of contamination. Owing to these limitations, Abraham and Parker [19] proposed a modified approach that takes into account all contamination factors for a specified set of pollutants, dividing the sum by the number of pollutants analyzed, including heavy metals [19] [20].

$$mC_d = \frac{\sum_{i=1}^{n} C_F}{n}$$

Here, n denotes the number of analyzed elements, i represents the element, and CF is the contamination factor. The average concentration of a metal requires the analysis of a minimum of three samples of contaminated sediments, with reference concentrations ("baseline") determined from uncontaminated sediments in the surrounding region [19] [21]. The classification of sediments based on their degree of contamination is presented in **Table 3**.

Table 3. Modified contamination degree class according to Abraham and Parker 2008.

Class	Value	Pollution intensity
1	$mC_d \le 1{,}5$	Zero to very low contamination degree
2	$1.5 < mC_d \le 2$	Low contamination degree
3	$2 < mC_d \le 4$	Moderate contamination degree
4	$4 < mC_d \le 8$	High contamination degree
5	$8 < mC_d \le 16$	Very high contamination degree
6	$16 < mC_d \le 32$	Extremely high contamination degree
7	$mC_d \ge 32$	Ultra-high contamination degree

2.7. Geoaccumulation Index (Igeo)

Table 4. Geo-accumulation index classes.

Class	Value	Pollution Intensity
0	$I_{geo} \le 0$	No pollution
1	$0 < I_{geo} \le 1$	From polluted to moderately polluted
2	$1 < I_{geo} \le 2$	moderately polluted
3	$2 < I_{geo} \le 3$	From moderately polluted to heavily polluted
4	$3 < I_{geo} \le 4$	Heavily polluted
5	$4 < I_{geo} \le 5$	From heavily polluted to extremely polluted
6	$5 < I_{geo}$	Extremely polluted

This method assesses sediment pollution levels resulting from anthropogenic heavy metal inputs within a specified area [14] [22] and calculates the *Igeo* value using the following equation [23]. It is a criterion for determining the level of metal pollution, developed by Müller in 1981 [24]. The method compares the metal concentration in the sediment under study with that of the local geological background, using the following formula:

$$I_{geo} = \log_2 \frac{C}{1{,}5Bn}$$

Here, *c* denotes the concentration of a metal in the sediment, and *Bn* denotes the concentration of the local geochemical background for the same metal. The factor 1.5 is used to account for natural fluctuations in the metal content of the sediments. These geo-accumulation index values facilitate the determination of pollution intensity, which ranges from class 0 to class 6 (**Table 4**). The mean concentration from the last three campaigns was used. The *Bn* values provided by Wedepohl [15] for the natural concentrations in the terrestrial environment were taken as a reference.

2.8. Statistical Analysis of Data

All metal concentrations were determined in mg·kg^{-1} on a dry weight basis. Our data do not follow a normal distribution, primarily due to the limited number of available samples within each variable group. Only non-parametric tests were used. All statistical analyses were conducted using Excel and RStudio. The "Nada" package was used to process data below the detection limit.

First, the Shapiro-Wilk test was applied to assess the normality of the data, and the Levene test was used to check for homogeneity of variances. Non-parametric Kruskal-Wallis and Wilcoxon tests were employed to evaluate differences between modalities. The Wilcoxon test is a non-parametric test used to compare two groups or matched samples. It is often used as an alternative to paired testing when the data do not meet the assumptions of normality or when the data are measured on an ordinal scale. The test is based on the ranks of observations in each group and compares the group medians.

These two tests helped identify which variables (year, campaign, season, location) had the greatest influence on the measured concentrations. Subsequently, the Kendall correlation test was employed to determine whether the different analyzed heavy metals originated from the same source. The results are presented in terms of p-values. The p-value is a number between 0 and 1, with a very small p-value indicating stronger evidence against the null hypothesis. Differences were considered significant if their p-values were less than or equal to 0.05.

3. Results

3.1. Trace Metal Content in the Reserve Sediments

Figure 2 presents the mean concentrations of cadmium, lead, and mercury in sediments from seven lakes after four sampling campaigns. The results demonstrate the presence of Cd, Pb, and Hg in all lakes. Cd levels are relatively homogeneous, ranging from 6.17 ± 6.3 mg·kg^{-1} at Lac Tigo to 8.34 ± 16.01 mg·kg^{-1} at Grand Lac. Lead, by contrast, displays considerable spatial variability, with concentrations ranging from 0.76 ± 0.54 mg·kg^{-1} at Lac Ethiopie to 4.18 ± 6.3 mg·kg^{-1} at Lac Kakhira. Mercury also shows some variation between lakes, with Lac Maristes 1 recording the highest levels (3.72 ± 7.42 mg·kg^{-1}), while Grand Lac and Lac Kakhira exhibit the lowest concentrations (2.15 ± 4.28 mg·kg^{-1}). Despite these variations, the Kruskal-Wallis test revealed that the spatial differences for all three trace metals were not statistically significant ($p \geq 0.05$).

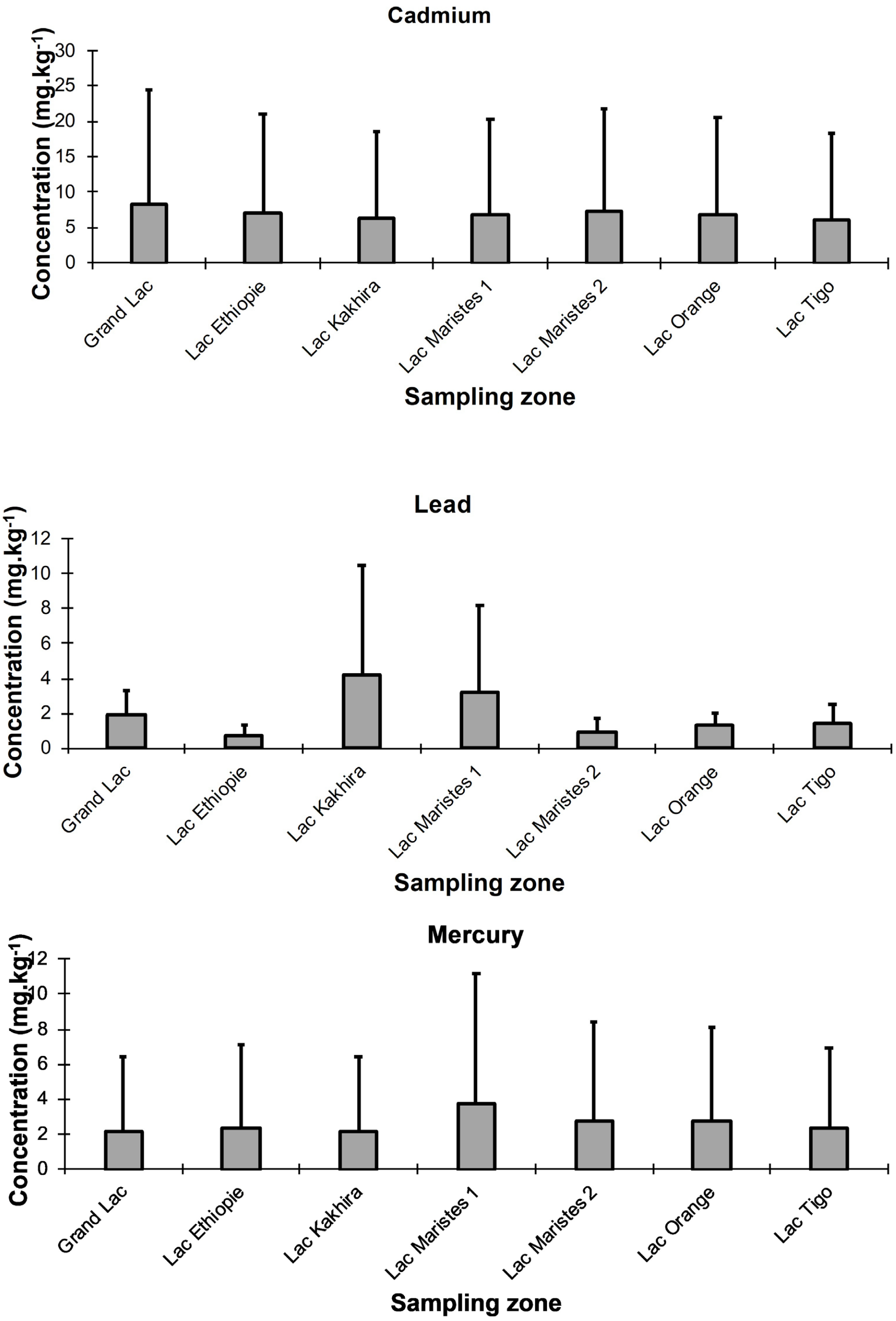

Figure 2. Average concentration of trace metallic elements between 2021-2023 in UNRPGND.

3.2. Spatio-Temporal Variation in Trace Metal Content of Sediments

3.2.1. Cadmium Concentration

Seasonal and inter-annual variations in cadmium concentrations across the lakes are illustrated in Figure 3. Cadmium levels exhibit pronounced seasonality, with concentrations ranging from 0.02 mg·kg^{-1} to 0.46 mg·kg^{-1} during the dry season, while significantly higher values, between 12.31 mg·kg^{-1} and 16.21 mg·kg^{-1}, are recorded in the wet season. Among all lakes, Grand Lac and Lac Maristes 2 consistently show the highest cadmium concentrations, irrespective of the season. Statistical analysis, notably the Kruskal-Wallis test, confirms these seasonal differences as highly significant (p = 5.194e − 05).

Regarding inter-annual variability, the results indicate substantial disparities between years. Cadmium concentrations in sediments are significantly higher in samples collected during the first year across all lakes. The Kruskal-Wallis rank test further supports these findings, revealing statistically significant differences between years (p = 0.002312).

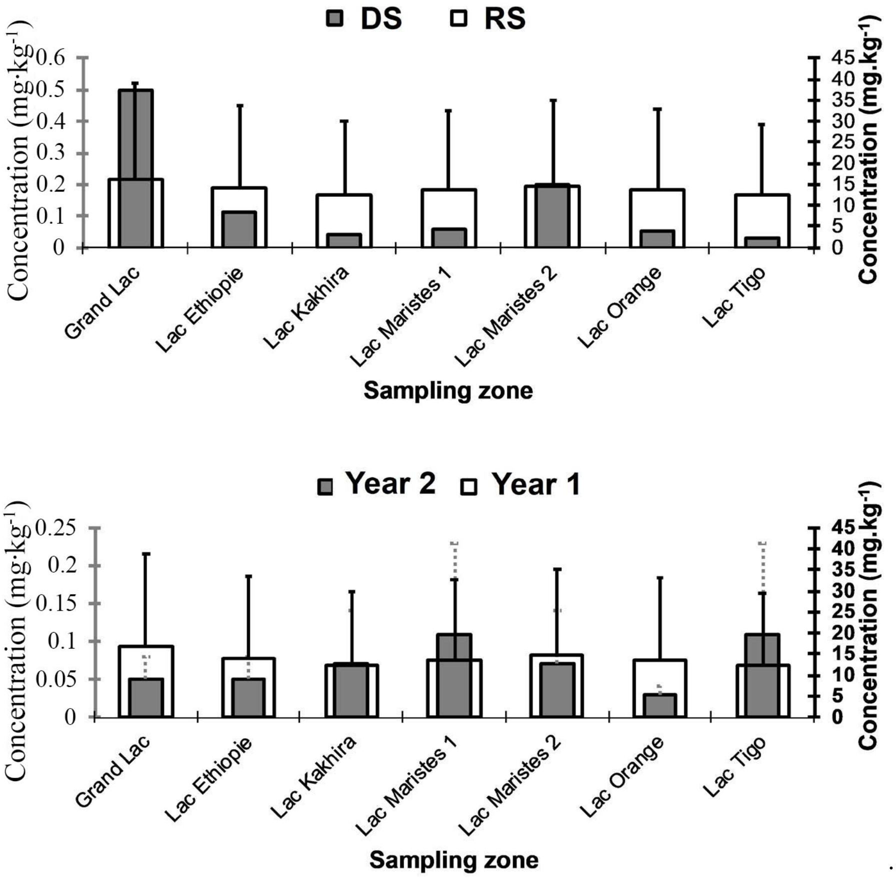

Figure 3. Spatiotemporal variations in Cd levels in the UNRPGN. DS = Dry season and WS = Wet season.

3.2.2. Lead Concentration

Seasonal and inter-annual variations in lead (Pb) concentrations across the lakes are illustrated in **Figure 4**. Pb levels exhibit a distinct seasonal pattern, with higher concentrations recorded during the wet season, ranging from 0.3 mg·kg^{-1} to 7.01 mg·kg^{-1} on average. The highest Pb levels during this period were observed at Lac Kakhira. In contrast, Pb concentrations are generally lower during the dry season, with more uniform averages across different lakes, varying from 0.3 mg·kg^{-1} at Lac Ethiopie to 5.45 mg·kg^{-1} at Lac Maristes 1. The Kruskal-Wallis rank test confirms a statistically significant difference between seasons (p = 0.01947).

Regarding inter-annual variability, the results reveal considerable differences between years. The highest Pb concentrations were observed during the first year of sampling, with Lac Kakhira recording an average of 7.97 mg·kg^{-1}, compared to only 0.395 mg·kg^{-1} in the second year. The Kruskal-Wallis test further confirms a significant difference between years (p = 0.01163).

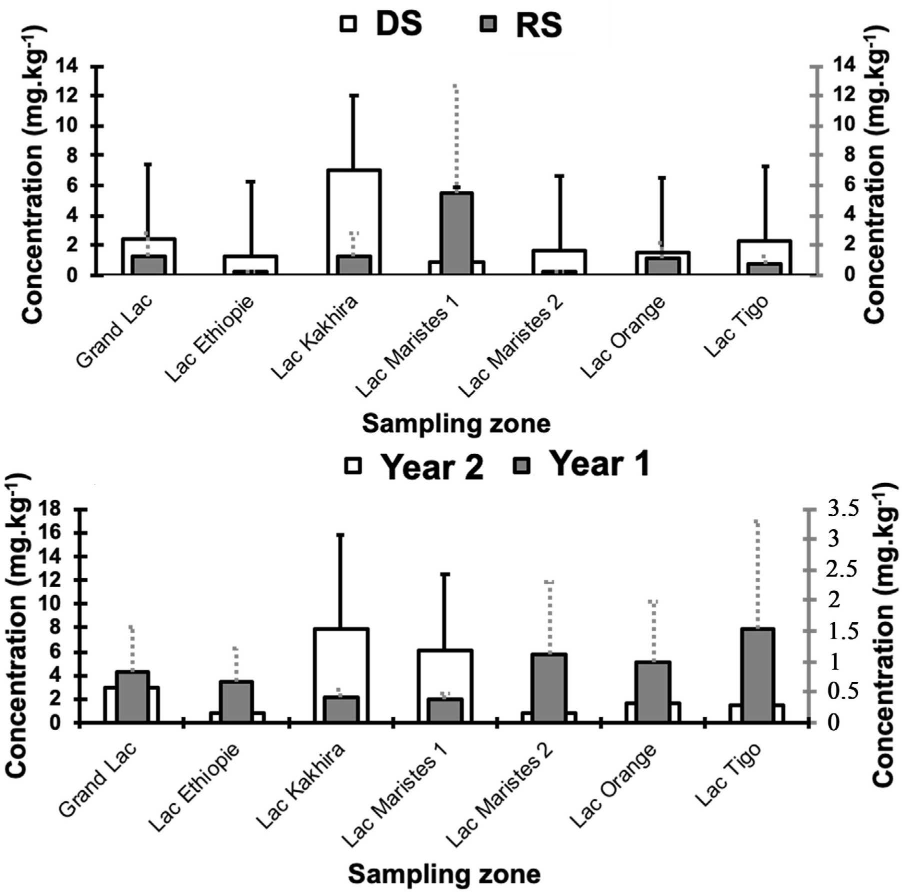

Figure 4. Spatiotemporal variations in Pb levels in the UNRPGN. DS = Dry season and WS = Wet season.

3.2.3. Mercury Concentration

Figure 5 illustrates the seasonal and inter-annual fluctuations in mercury (Hg) levels across the lakes. Mercury concentrations exhibit pronounced seasonality, with relatively low levels during the dry season. At several sites, including Lac Kakhira, Grand Lac, Lac Tigo, Lac Ethiopie, and Lac Maristes 2, Hg was undetectable, while the highest recorded value was 0.025 mg·kg^{-1} at Lac Orange. In contrast, during the wet season, mercury concentrations rise significantly, reaching a peak of 7.43 mg·kg^{-1} at Lac Maristes 1. Other sites also display elevated Hg levels, frequently surpassing established safety thresholds. Statistical analysis, notably the Kruskal-Wallis rank test, did not reveal significant differences between seasons (p = 0.06779). However, inter-annual variability showed notable disparities (p = 5.868e−05).

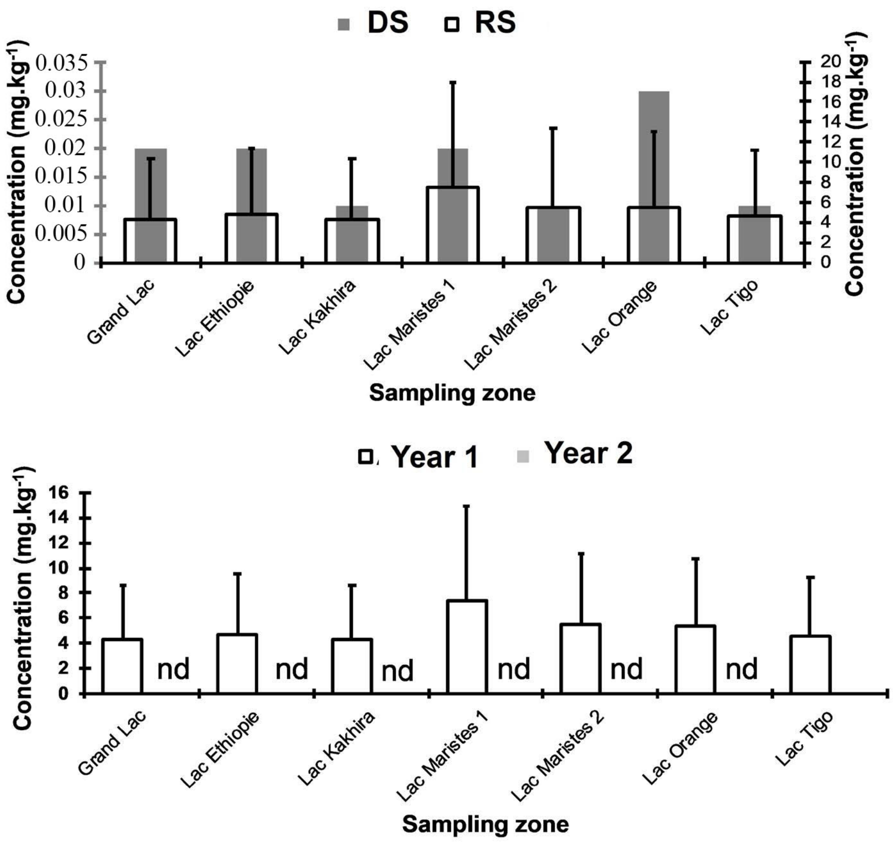

Figure 5. Spatiotemporal variations in Hg levels in the UNRPGN. DS = Dry season and WS = Wet season.

3.3. Assessment of Sediment Quality

The contamination factor reveals very strong sediment contamination in different lakes (CF ≥ 6) for cadmium and mercury. The highest cadmium levels are observed at Grand Lac and Lac Maristes 2. For mercury, the highest values are recorded at Lac Maristes 1 and Lac Maristes 2. In contrast, for lead, the contamination factor remains below 1, indicating very low or even negligible pollution.

Table 5 presents the modified contamination degree values, which assess the intensity of polymetallic pollution and classify the different sites. The obtained values all exceed 32, indicating that the sediments in all lakes exhibit an ultra-high level of contamination. Among them, Lac Maristes 1 and Lac Maristes 2 are identified as the most polluted sites.

Table 5. CF and mCd values in the different lakes.

		Grand Lac	Lac Kakhira	Lac Ethiopie	Lac Tigo	Lac Orange	Lac Maristes 1	Lac Maristes 2
Cf	Pb	0.11	0.25	0.05	0.1	0.08	0.09	0.56
	Cd	92.61	69.42	78.35	68.53	76.09	75.78	81.11
	Hg	51.2	51.14	56.44	55.07	64.41	88.52	66.2
mCd		47.97	40.27	44.95	41.23	46.86	54.80	49.29

Table 6 shows the geo-accumulation index values calculated for the different sites. There appears to be strong sediment contamination in the reserve by cadmium, with geo-accumulation index values greater than 5. However, Igeo values for lead indicate that it does not currently pose a threat to the reserve's ecosystem.

Table 6. Geo-accumulation index values.

		Grand Lac	Lac Kakhira	Lac Ethiopie	Lac Tigo	Lac Orange	Lac Maristes 1	Lac Maristes 2
Igeo	Pb	−3.39	−2.21	−4.8	−3.77	−3.93	−2.61	−4.57
	Cd	6.18	5.76	5.94	5.74	5.89	5.89	5.99
	Hg	5.09	5.09	5.23	5.19	5.42	5.88	5.46

4. Discussion

This study is the first to document cadmium (Cd) and mercury (Hg) contamination in sediments of the Urban Natural Reserve of Pikine and Guédiawaye Niayes District (UNRPGND), Senegal, while lead (Pb) levels remain below natural thresholds. These findings align with global patterns of heavy metal pollution in freshwater ecosystems, where Cd and Hg are frequently associated with anthropogenic activities such as industrial discharges, agricultural runoff, and atmospheric deposition [25]-[27]. However, the specific contamination patterns in the UNRPGND reflect local environmental and anthropogenic factors, necessitating a detailed comparison with international studies to contextualize the results and inform management strategies.

4.1. Seasonal and Inter-Annual Variations

Cd concentrations in the UNRPGND exhibited pronounced seasonal variation, with significantly higher levels during the wet season (12.31 - 16.21 mg kg^{-1}) compared to the dry season (0.02 - 0.46 mg kg^{-1}). This pattern is consistent with studies in other regions, such as Poyang Lake in China, where Dai *et al.* [28] reported elevated Cd levels during the wet season due to runoff from agricultural and urban areas. Similarly, El-Amier *et al.* [14] observed increased heavy metal concentrations in Egypt's Burullus Lake during periods of high rainfall, attributing this to the mobilization of contaminants from surrounding catchments. In the UNRPGND, the wet season likely exacerbates Cd transport from phosphate fertilizers and industrial effluents, which are prevalent in Senegal's urbanizing landscapes [10] [29]. Inter-annual variability, with higher Cd concentrations in the first year of sampling, may reflect fluctuations in rainfall intensity, sediment resuspension, or changes in industrial activity, as noted in other freshwater systems [30] [31].

Hg concentrations also showed marked seasonality, with undetectable levels at several sites during the dry season and peaks up to 7.43 mg kg^{-1} at Lac Maristes 1 during the wet season. This trend mirrors findings in Baiyangdian Lake, China, where Ji *et al.* [32] linked elevated Hg levels to runoff and atmospheric deposition during monsoon periods. In the UNRPGND, Hg inputs are likely exacerbated by urban runoff and industrial emissions, as observed in coastal ecosystems of Dakar [4]. The absence of detectable Hg during the dry season may be due to sediment burial or reduced runoff, a phenomenon also reported in semi-arid watersheds influenced by mercury sources [33].

In contrast, Pb concentrations showed minimal seasonal variation, with slightly higher levels during the wet season (0.3 - 7.01 mg kg^{-1}) compared to the dry season (0.3 - 5.45 mg kg^{-1}). This stability aligns with studies in urbanized regions, such as Nanjing, China, where Liu *et al.* [34] attributed consistent Pb levels to chronic inputs from vehicular emissions and atmospheric deposition, which are less dependent on seasonal runoff. In the UNRPGND, the low Pb contamination (CF < 1) suggests limited industrial or vehicular sources compared to highly urbanized areas like the Rhine River, where Müller [25] reported significant Pb accumulation due to industrial discharges.

4.2. Sources of Contamination

The high Cd contamination in the UNRPGND is likely driven by anthropogenic sources, including phosphate fertilizers, industrial effluents, and mining activities, as highlighted by Roberts [29] and Suciu *et al.* [35]. The strong affinity of Cd for organic matter and fine-grained sediments explains its persistence in the reserve's lake environments, a characteristic also observed in Baiyangdian Lake [32] and Tobruk Bay, Libya [36]. In Senegal, the widespread use of phosphate fertilizers in agriculture, coupled with urban runoff from and Guédiawaye, likely contributes to Cd enrichment, particularly during the wet season [10].

Hg contamination, with contamination factors (CF ≥ 6) at Lakes Maristes 1 and 2, points to significant anthropogenic inputs, potentially from industrial emissions, artisanal mining, or municipal waste disposal. These sources are consistent with global patterns, as seen in the Rio Doce Estuary, Brazil, where Fabrício *et al.* [21] linked Hg pollution to industrial and mining activities. In the UNRPGND, the proximity of urban and industrial zones to the reserve may exacerbate Hg deposition, particularly through atmospheric transport and runoff, as reported in the Atlantic Ocean by Mason *et al.* [37]. The high CF values for Hg suggest a need for targeted source identification, as recommended by Zhu *et al.* [24] for Northeast China's reservoir sediments.

The low Pb concentrations in the UNRPGND contrast sharply with heavily industrialized regions, such as the Changjiang Estuary, China, where He *et al.* [12] reported elevated Pb levels due to urban and industrial discharges. The minimal Pb contamination in the reserve indicates a relatively low influence from vehicular or industrial sources, possibly due to effective waste management or limited industrial activity in the immediate vicinity. However, continuous monitoring is essential to prevent future Pb accumulation, as changing environmental conditions could lead to remobilization, as warned by Maar *et al.* [38].

4.3. Ecological and Health Risks

The high contamination factors for Cd and Hg (CF ≥ 6) classify these metals as major pollutants in the UNRPGND, posing significant ecological and health risks. Cd's toxicity, even at low concentrations, threatens aquatic life through bioaccumulation, as demonstrated by Ali *et al.* [22] in global freshwater ecosystems. In the UNRPGND, elevated Cd levels in sediments likely contribute to bioaccumulation in benthic organisms and fish, increasing risks for human populations consuming local fish, as reported by Diop *et al.* [5] in Dakar's ponds. This pattern is comparable to Burullus Lake, Egypt, where El-Amier *et al.* [14] documented Cd bioaccumulation in fish, leading to potential human health risks via dietary exposure.

Hg's ability to form methylmercury (MeHg) in aquatic environments amplifies its ecological and health impacts. The elevated Hg levels in the UNRPGND, particularly at Lac Maristes 1, suggest a high potential for MeHg production, which can bioaccumulate in the food web, as noted by Driscoll *et al.* [39] and Jeong *et al.* [40]. Similar risks have been observed in the Liaohe River, China, where Wang *et al.* [41] linked Hg contamination to increased MeHg in fish, posing severe risks to human consumers. In the UNRPGND, the consumption of fish from contaminated lakes could lead to neurological and developmental health issues, particularly for vulnerable populations, as highlighted by Scheuhammer *et al.* [42].

The geo-accumulation index (Igeo) for Cd (Igeo > 5) indicates extreme pollution, comparable to levels reported in Poland's river sediments by Sojka *et al.* [27], where industrial and agricultural inputs drove severe contamination. In contrast, the low Igeo values for Pb suggest minimal ecological impact, aligning with findings in less industrialized wetlands, such as those described by Knox *et al.* [43]. These contrasting patterns underscore the need for targeted mitigation strategies focusing on Cd and Hg.

4.4. Implications for Environmental Management

The severe Cd and Hg contamination in the UNRPGND, exceeding safety thresholds in several lakes, necessitates urgent monitoring and remediation efforts. The high Igeo values for Cd highlight the need for source control measures, such as regulating phosphate fertilizer use and improving industrial wastewater treatment, as recommended by Suciu *et al.* [34]. Phytoremediation, as explored by Fournon [44], could be a cost-effective strategy for reducing Cd levels in sediments, particularly in the reserve's vegetated areas.

For Hg, mitigation should focus on reducing atmospheric deposition and runoff from urban and industrial sources. The Ramsar Convention Secretariat [45] emphasizes the importance of integrated wetland management to protect ecosystems like the UNRPGND, which provide critical services such as water purification and biodiversity support. International examples, such as the constructed wetlands studied by Knox *et al.* [43], demonstrate the potential of engineered solutions to remove heavy metals over long periods.

Continuous monitoring of Pb is also warranted, as environmental changes, such as increased urbanization or sediment disturbance, could lead to future contamination, as observed in estuaries by Ridgway & Shimmield [11]. Community-based monitoring programs, coupled with public awareness campaigns, could help reduce anthropogenic inputs, as suggested by Saidon *et al.* [46]. Furthermore, risk assessments integrating sediment, water, and biota data, as conducted by Islam *et al.* [47] in Bangladesh, are essential to evaluate the full scope of contamination and inform policy.

5. Conclusion

The findings of this study underscore the urgent need for strengthened environmental monitoring and regulation in urban wetland reserves. While cadmium and mercury were identified as major contaminants due to their elevated concentrations and high contamination factors, lead contamination remained relatively low. These results highlight the complexity and site-specific nature of sediment pollution, influenced by both seasonal dynamics and inter-annual variability. Future research should focus on pinpointing the precise sources of metal inputs and assessing the ecological impacts of their accumulation. Such efforts are vital for informing evidence-based management strategies and ensuring the protection of biodiversity and public health in these vulnerable aquatic ecosystems.

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Conflicts of Interest

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

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