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Assessment of the Ecological Risk Associated with Seasonal Variability in Water and Sediment Contamination by Heavy Metals along the Coast of Senegal

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Abstract

Pollution of water and sediment by heavy metals (HMs) poses a significant threat to aquatic ecosystems due to their toxicity and persistence. This study aimed to evaluate the ecological risk associated with the seasonal and spatial variation in heavy metals concentrations in the water column and sediments across five sites along the Senegalese coastline. Water and sediment samples were collected using standardized methods and analyzed for HMs by flame atomic absorption spectrophotometry (AAS) after acid digestion. The highest mean concentrations of HMs in water were as follows: Pb (0.96 mg/L) > Fe (0.76 mg/L) > Cr (0.47 mg/L) > Cd (0.20 mg/L) > Cu (0.08 mg/L) > Mn (0.06 mg/L) and in sediments: Fe (442.38 mg/kg) > Pb (44.51 mg/kg) > Mn (27.65 mg/kg) > Cr (16.55 mg/kg) > Cu (16.31 mg/kg) > Cd (3.75 mg/kg). In water, the concentrations of Pb, Cd, and Cr exceeded the 2012 USEPA threshold values across all sites and seasons. In contrast, in sediments, most HMs were below the reference values in the sediment quality guidelines, except of the Soumbédioune site during the dry season where Cd exceeded the probable effect limit (PEL). Assessment using the enrichment factor (EF), geo-accumulation index (Igeo) and contamination factor (CF) indicated moderate to high levels of pollution that Pb, Cd and Cr had, while Mn, Cu and Fe showed low pollution levels. The ecological risk index also showed that, regardless of the season, only the Rufisque and Soumbédioune sites presented a moderate risk; the other sites are classified as low risk. Principal component analysis (PCA)

reveals that during the dry season, in water and sediments, the Soumbédioune site is more impacted by Cd, while Rufisque has higher Pb levels. This study could serve as a reference for monitoring water and sediment quality along the Senegalese coast in view of the urbanization and industrialization of Senegal's coastal cities.

Keywords

Heavy Metals, Potential Ecological Risk, Seasonal Variation, Coastline, Senegal

1. Introduction

The coastal ecosystem is one of the most important ecosystems on the planet [1]. It facilitates essential exchanges, particularly with regard to biodiversity, food production, and ecological well-being [2]; It is therefore crucial to preserve the quality of their habitat and their ecological migration. However, human activities such as urbanization, agricultural runoff, industrial effluents, and chemical spills have seriously threatened coastal ecosystems [2] [3]. These human activities are the main cause of increased pollution from heavy metals in these ecosystems [4]. Heavy metals (Pb, Cd, Hg), due to their persistence, non-biodegradability, and toxicity, are considered major pollutants in marine environments, threatening the health of marine organisms and aquatic ecosystems [5]-[7].

Heavy metals found in aquatic ecosystems are adsorbed by suspended sediments via atmospheric deposition, rain washout, and surface runoff [8] [9]. Thus, sediments are capable of acting both as a reservoir and as a potential source of heavy metals release into water [10]. Once accumulated in sediments, these heavy metals can be remobilized through changes in certain environmental parameters such as pH, dissolved oxygen, and salinity, thereby causing secondary contamination [11]. To this end, sediments and water are widely used in monitoring contamination by heavy metals in coastal areas [8] [12].

The Senegalese coastline stretches for approximately 706.72 km. It consists of a diverse and rich ecosystem due to the presence of the Canary Current. However, anthropogenic pressure around this area is intensifying every day. The rapid development of urban and industrial activities, combined with inefficient wastewater management, has led to the introduction of heavy metals into the Senegalese marine environment, threatening its ecological balance [13]. Heavy metals have therefore become one of the main pollutants of seawater and the sedimentary environment [13]. However, there are few studies on metal pollution in Senegal's coastal and marine environment. Studies have reported heavy metals concentrations in water and sediments and toxicological assessments of edible marine organisms harvested in areas polluted by these compounds [14]-[17]. However, few studies have focused on seasonal and spatial variation in heavy metals contamination along the Senegalese coast. Therefore, the present study aimed to establish seasonal and spa-

tial monitoring of heavy metals pollution (Pb, Cd, Cu, Cr, Mn, and Fe) in water and sediments at five sites along the Senegalese coastline.

2. Materials and Method

2.1. Study Area and Sampling

Senegal is a coastal country located in West Africa between 12˚80" and 16˚41"N and 11˚21" and 17˚32"W [14]. Its coastline includes the westernmost part of the African continent. In the sampling area, the climate, which is of the Sudano-Sahelian type, is characterized by a long dry season, cool from November to March (dry-cold season, DCS) and hot from April to June (dry-hot season), and by a short hot-wet season from July to October. Total annual rainfall varies from 263 mm (Saint Louis) to 412 mm (Dakar) [14]. Five sampling sites (**Figure 1**) were selected to represent a large part of the coastline, but also based on their degree of anthropization. The sites of Rufisque (Ru), Soumbédioune (So), and Hann (Hn), located near the city of Dakar, are characterized by high urban activity and significant domestic and/or industrial waste. The Saint Louis (St) site is located near the mouth of the Senegal River, which carries many pollutants, and the Kayar (Ky) site is some distance from significant anthropogenic influences and serves as our reference point.

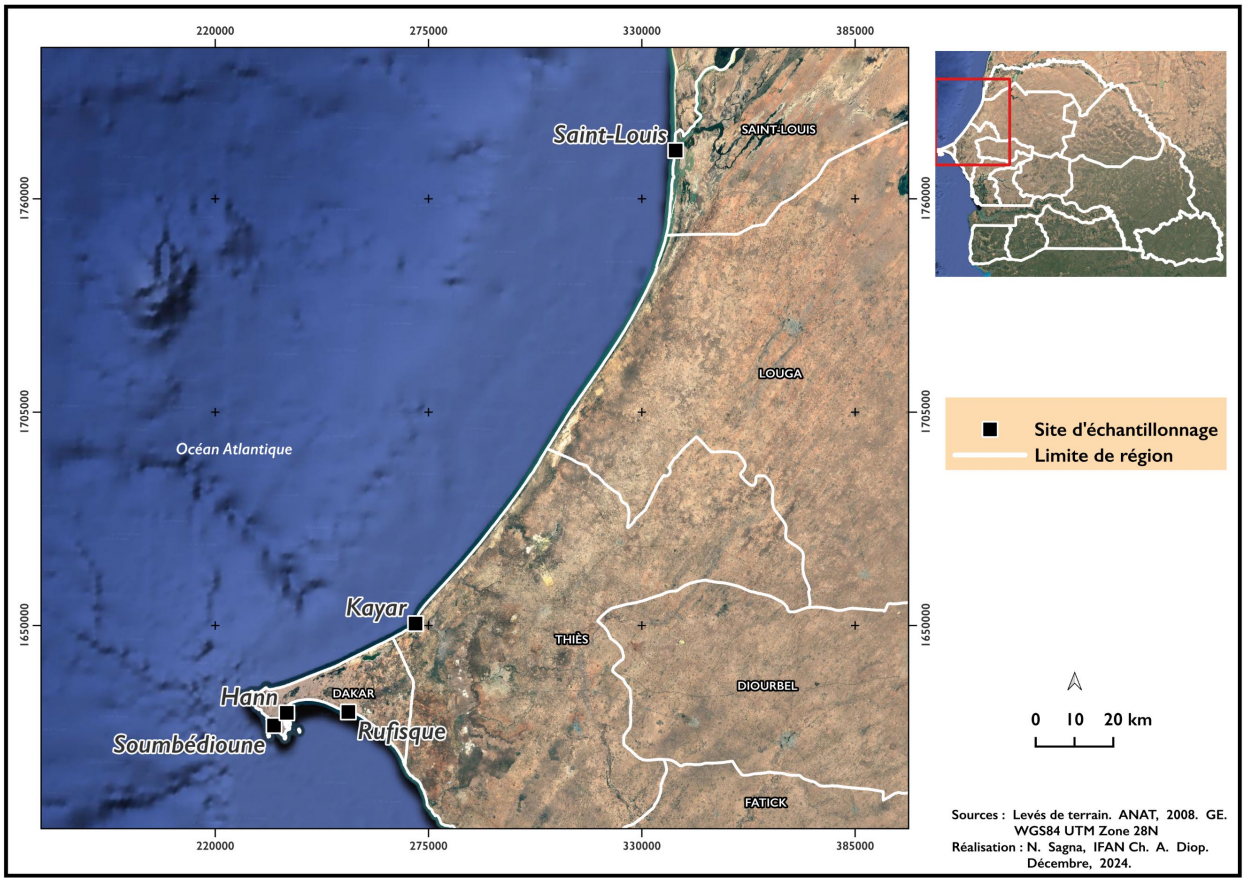

Figure 1. Map showing sampling sites along the Senegalese coast.

Sampling campaigns were carried out in September 2022 (wet season) and May 2023 (dry season), allowing for an assessment of the impact of climatic variations on the parameters studied. For each site and each season, three independent water samples were collected in new polyethylene bottles. Surface sediments were sampled in duplicate at the same location as the water samples using sterile polyethylene bags. After collection, the samples were placed in refrigerated coolers (4˚C) and then transported to the laboratory for processing and storage until analysis.

2.2. Sample Processing and Analysis

2.2.1. Measurement of the Physical and Chemical Parameters of Water

pH, salinity, temperature, and dissolved oxygen were measured in surface water in situ using a SANXIN Model SX736 pH/mV/Cond/DO meter equipped with a pH electrode, a temperature and salinity electrode, and an oxygen probe. To measure these parameters, the specific electrode connected to an electronic reader that serves as a monitor is immersed in the water at a depth of at least 1 m until a stable measurement value is obtained. The pH are calibrated in the laboratory using pH = 4, pH = 7, and pH = 10 standard solutions, respectively. The various electrode calibration standards were supplied with the device at the time of purchase.

2.2.2. Determination of Heavy Metals in Water

Water samples were filtered using Alltech microfiber filters with a porosity of 0.45 µm according to the APHA method [18]. The filtered samples are acidified with a few drops of 69% nitric acid before being analyzed for Pb, Cd, Cu, Mn, Fe, and Cr by flame AAS.

2.2.3. Determination of Heavy Metals in Sediments

Heavy metals in sediments were analyzed according to the protocol described by APHA [18]. To do this, 1 g of dry sediment sieved to 63 µm was placed in vials and then digested in a mixture of 69% HNO_3/37% HCl (1/3 v:v). Following this step, the vials were placed on a hot plate for approximately 1 hour until white vapors were released. The recovered solutions were diluted to 50 ml with deionized water and then analyzed by flame AAS.

2.3. Assessment of Sediment Pollution

The environmental impact of heavy metals was assessed by determining the enrichment factor (EF), geo-accumulation index (Igeo), contamination factor (CF), degree of contamination (C_{deg}), and potential ecological risk index (RI) of the sediment for each study site.

2.3.1. Geo-Accumulation Index (Igeo)

The geoaccumulation index is widely used in studies of heavy metals in sediments and soils. It assesses sediment contamination by comparing concentrations at the site with those in a reference or control sediment [19]. To measure the degree of contamination by heavy metals in the sediments in our study, the Igeo was calcu-

lated using Equation (1) [20]:

$$\text{Igeo} = \log_2 \frac{C_n}{1.5B_n} \quad (1)$$

C_n (mg/kg) is the concentration of metal n in the sediment studied, B_n (mg/kg) is the geochemical background of elements n defined by [21]. The factor 1.5 represents the influence of geological and deposit characteristics, it reduces the effect of human activities, and is applied as a correction factor for anthropogenic influence in the calculation.

According to Muller's classification, Igeo can be divided into seven classes: Class 0 (practically uncontaminated): Igeo < 0; Class 1 (uncontaminated): 0 < Igeo < 1; Class 2 (moderately contaminated): 1 < Igeo < 2; Class 3 (moderately to heavily contaminated): 2 < Igeo < 3; Class 4 (heavily contaminated): 3 < Igeo < 4; Class 5 (heavily to extremely contaminated): 4 < Igeo < 5; Class 6 (extremely contaminated): 5 < Igeo. The concentrations of elements in class 6 can be a hundred times higher than the geochemical background value [20].

2.3.2. Enrichment Factor

A standardized enrichment factor is used to assess the degree of anthropogenic pollution by heavy metals in sediments [22]. This involves normalizing sediments relative to reference elements such as Fe, Al, Li, Sc, Ti, Ga, and Zn [23]-[26]. Thus, in this study, Fe was chosen as the standardization element because of its exclusively lithospheric origin [27] in order to define the enrichment factor FE of a given metal element in the sediment. The following Equation (2) was used to calculate the enrichment factor:

$$\text{EF} = \left(C_n / C_{\text{Fe}}\right)\text{sediment} \Big/ \left(C_n / C_{\text{Fe}}\right)\text{reference} \quad (2)$$

where (C_n/C_{Fe}) sediment represents the ratio between the concentration of element n (C_n) and that of Fe (C_{Fe}) in the sediment sample (mg/kg) and (C_n/C_{Fe}) represents the same ratio in a reference sediment (mg/kg). This contamination classification was used to determine the enrichment level of the different sediments: 2 < EF < 5 deficient to moderate enrichment, EF = 5 - 10 moderately severe enrichment, EF = 10 - 25 severe enrichment, EF = 25 - 50 very severe enrichment, and EF > 50 extremely high enrichment [28].

2.3.3. Contamination Factor and Degree of Contamination

The overall level of sediment contamination by heavy metals is assessed by the contamination factor (CF). It has been classified and determined using Equation (3):

$$\text{CF}_n = \frac{C_\eta}{C_m} \quad (3)$$

where C_n (mg/kg) represents the concentration of heavy metals in a sediment sample and C_m (mg/kg) represents the reference sediment value [29]. CF concentrations were interpreted according to the classification of [29]: low contamination at CF < 1; moderate contamination at 1 ≤ CF < 3; considerable contamination at

$3 \leq CF < 6$; and very high contamination at $CF > 6$.

The degree of contamination C_{deg} was calculated using Equation (4) as described by [29]. It allows the level of pollution at sites to be determined by adding up the contamination factors of the heavy metals found.

$$C_{deg} = \sum_1^n CF_i \tag{4}$$

2.3.4. Potential Ecological Risk Index

The ecological risk assessment of heavy metals in sediments was carried out by measuring the potential ecological risk index. It was initially introduced by [29] and is given by the following Equation (5):

$$RI = \sum_0^n E_r^n = \sum_0^n T_r^n CF_n \tag{5}$$

where E_r is the potential ecological risk coefficient and T_r is the toxicity factor of an element. For this study, the T_r values of the elements Cu = Pb = 5, Cr = 2 and Cd = 30 were used. The PERI of heavy metals was categorized into five levels (**Table 1**).

Table 1. Classification of potential ecological risk.

E_r		RI	
Level	Classification	Level	Classification
$E_r^n < 40$	Low risk	RI < 150	Low Ecological risk
$40 \leq E_r^n < 80$	Moderate risk	150 ≤ RI < 300	Moderate ecological risk
$80 \leq E_r^n < 160$	Considerable risk	300 ≤ RI < 600	Significant ecological risk
$160 \leq E_r^n < 320$	High risk	RI ≥ 600	Very high ecological risk
$E_r^n \geq 320$	Very high risk	-	-

2.4. Statistical Analysis

The data were recorded and statistically processed using Microsoft Excel 2019 and SPSS 24.0.12 (Statistical Package for the Social Sciences). The analysis of seasonal and spatial variations in metal concentrations in water and sediment samples from the five sites was performed using a one-factor ANOVA. In the case of sediments, the duplicates were analyzed independently and the data were averaged during statistical analysis, whereas the three water replicates were treated as independent samples. When the data did not meet the parametric assumptions of normality and homogeneity of variance, the nonparametric Kruskall Wallis test followed by Dunn's test for pairwise comparisons was applied. A t-test was used to observe significant differences in element concentrations between the wet season and the dry season. The significance level for differences in critical values was set at $p < 0.05$. Spearman's analytical correlation method was used for the multipair comparison of the correlation level between heavy metals. Principal component analysis (PCA) was used to explore the relationships between sites and element concentrations in water and sediments.

3. Results and Discussion

3.1. Physicochemical Parameters of Water

The results of the physicochemical analysis of water samples presented in **Table 2** show pH values ranging from 6.91 (Ru) to 7.62 (Ky) during the dry season, and from 6.56 (Hn) to 7.76 (Ru) during the wet season. The water pH exhibited a character ranging from slightly acidic to moderately alkaline. Overall, the mean values fall within the recommended range (6.3 - 8.3) for seawater pH limits [30]. pH is a parameter that determines several physicochemical equilibria [31]. It is one of the most important factors affecting the mobility and potential ecological risk of heavy metals [32]. In general, metal mobility in the environment increases with decreasing pH due to the precipitation of metals as hydroxides, carbonates, or the formation of insoluble organic complexes [32]-[34].

The mean salinity indicate that the lowest salinity level (10.33 ppt) was recorded at the Hn site during the wet season, while the highest salinity (35.43 ppt) was observed at the Ky site during the dry season. Rainfall can reduce water salinity during the wet season conversely, due to high evaporation in the dry season, salinity can increase [30]. Indeed, increased rainfall causes a substantial influx of freshwater into the coastal zone from the river system, thereby lowering salinity.

Dissolved oxygen is one of the parameters most sensitive to pollution and serves as a good indicator of water quality. It plays a crucial role in the self-purification of surface waters and in sustaining aquatic life [30]. Measured dissolved oxygen concentration range from 1.16 mg/L (Hn) to 5.31 mg/L (Ru) in the dry season, and from 3.12 mg/L (Hn) to 14.38 mg/L (Ky) in the wet season. The decrease in dissolved oxygen at the Hn site can be explained by the decomposition of domestic and industrial organic matter discharged and accumulated there, contributing to notable drop in water oxygenation [35]. During the wet season, oxygen concentrations tend to increase in surface waters, as rainfall saturates the water with oxygen upon falling.

Table 2. Physicochemical parameters of coastal waters during two seasons (dry and wet).

	Saison	pH	Sal (ppt)	DO (mg/l)	Temp (˚C)
Ru	Dry	6.91 ± 0.06	32.71 ± 0.15	5.31 ± 0.19	25.20
	Wet	7.76 ± 0.05	11.81 ± 0.19	7.98 ± 0.03	33.20
So	Dry	7.57 ± 0.21	31.93 ± 0.25	5.43 ± 0.21	25.27
	Wet	7.43 ± 0.07	11.50 ± 0.22	3.87 ± 0.03	31.00
St	Dry	7.60 ± 0.10	33.53 ± 0.08	9.48 ± 0.86	24.17
	Wet	7.74 ± 0.05	11.07 ± 0.15	9.07 ± 0.72	31.00
Hn	Dry	6.93 ± 0.03	30.97 ± 0.33	1.16 ± 0.16	24.40
	Wet	6.56 ± 0.22	10.33 ± 0.31	3.12 ± 0.11	31.37
Ky	Dry	7.62 ± 0.03	35.43 ± 0.12	5.33 ± 0.26	23.10
	Wet	7.69 ± 0.09	15.63 ± 0.32	14.38 ± 0.11	29.07

3.2. Seasonal Variation in the Level of Heavy Metals Contamination in Water

Results show a statistically significant decrease ($p < 0.01$) in Pb concentrations across all sites during the wet season compared to the dry season (Figure 2). The highest Pb concentration was observed at the Ru site during both seasons, measuring 0.96 mg/L in the dry season and 0.66 mg/L in the wet season. The decrease in average Pb concentrations during the wet season could be attributed to the effects of precipitation, which may enhance leaching processes and contribute to the dilution of heavy metals during the rainy season [36] [37]. Furth more, the high Pb levels recorded at the Ru site may be attributed to industrial wastewater discharges at this site [38]. The average Pb concentrations in waters across all sites exceed the permissible limit set by the USEPA, which is 0.05 mg/L [39].

These concentrations are also higher than those reported by Diop *et al.*, who evaluated contamination, distribution, and speciation of heavy metals in the water column off the coast of Dakar, where total Pb ranged from 0.047 to 3.87 µg/L [13]. The Pb concentrations recorded in this study exceed those found by Kouaménan *et al.*, who obtained 6.03 µg/L of Pb in the dry season and 6.66 µg/L in the wet season in the Ebrié lagoon, Côte d'Ivoire [40]; by Azdem *et al.*, who recorded Pb values ranging from 20 to 85 µg/L in seawater off the coast of Agadir in Morocco [41]; and by Ahmed *et al.*, who found Pb values between 1.61 and 5.84 µg/L in summer surface waters of the Red Sea, Egypt [42].

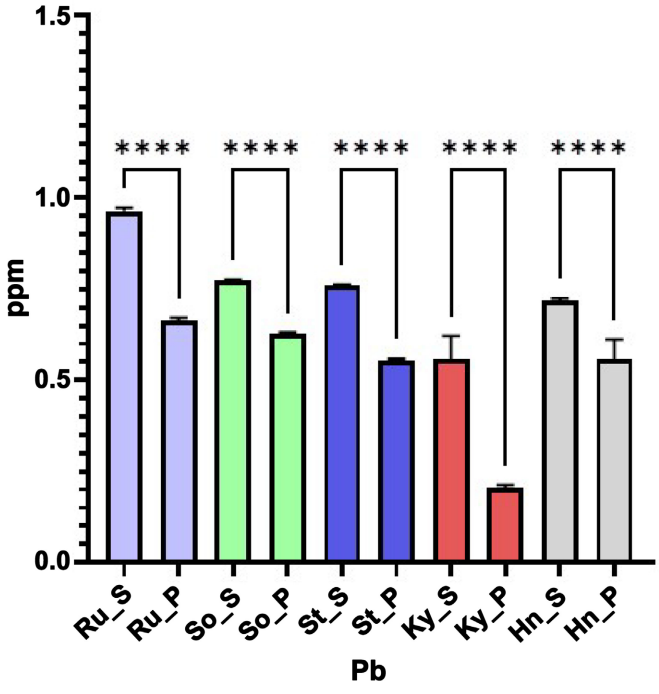

Figure 2. Mean Pb concentrations expressed in mg/L in water.

The Cd concentrations in waters at the different study sites are presented in Figure 3. Overall, Cd levels at all sites were low during the wet season, with a signif-

icant decrease ($p < 0.01$) between the two seasons at the Ru, So, and Ky. The highest Cd concentrations were obtained at the So site, followed by Ru and Ky during the dry season, with values of 0.20 mg/L, 0.16 mg/L, and 0.12 mg/L, respectively, while the lowest concentration (0.05 mg/L) was found at Ky during the wet season. The Cd values found in the water exceed the USEPA permissible standard of 0.005 mg/L [39]. They are also higher than those reported by Diop *et al.*, who recorded 0.43 µg/L of Cd in the water column off Dakar [13]; by Azdem *et al.*, who found Cd values ranging from 10 to 70 µg/L in seawater off the Agadir coast in Morocco [41] and Ahmed *et al.*, who obtained Cd concentrations between 0.16 and 0.41 µg/L in summer and 0.23 - 0.42 µg/L in spring in surface waters of the Red Sea in Egypt [42].

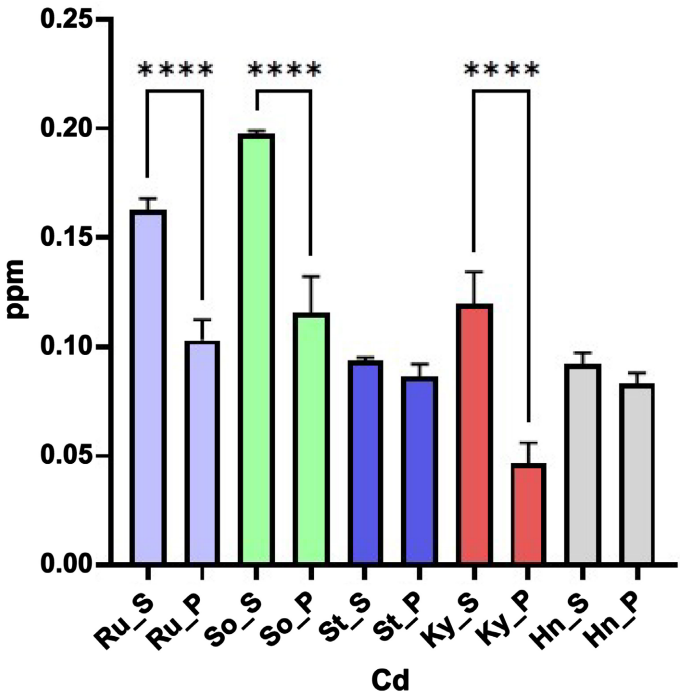

Figure 3. Mean Cd concentrations expressed in mg/L in water.

The highest Cr concentration of 0.47 mg/L was recorded during the dry season in Ky (**Figure 4**). The Cr values obtained exceed the USEPA standard of 0.05 mg/L [39]. They are also higher than those reported by Diop *et al.*, who found 4.56 µg/L in the water column off the coast of Dakar [13]. High Cr concentrations at the Ky site may indicate contamination of the geochemical background relative to the content of the Earth's crust [43]. However, the values found show no significant difference ($p > 0.05$) between seasons, suggesting a natural origin of Cr in the water of the different study sites.

The highest Cu concentrations were recorded at the Ky and Hn sites during the dry season, with a significant decrease ($p < 0.05$) in the wet season, reaching as low as 0.02 mg/L at the Hn site (**Figure 5**). Overall, the Cu concentrations obtained are below the tolerable limit set by the USEPA [39] but higher than those

found in the water column off Dakar [13] and in surface waters of the Red Sea in Egypt during summer and spring [42].

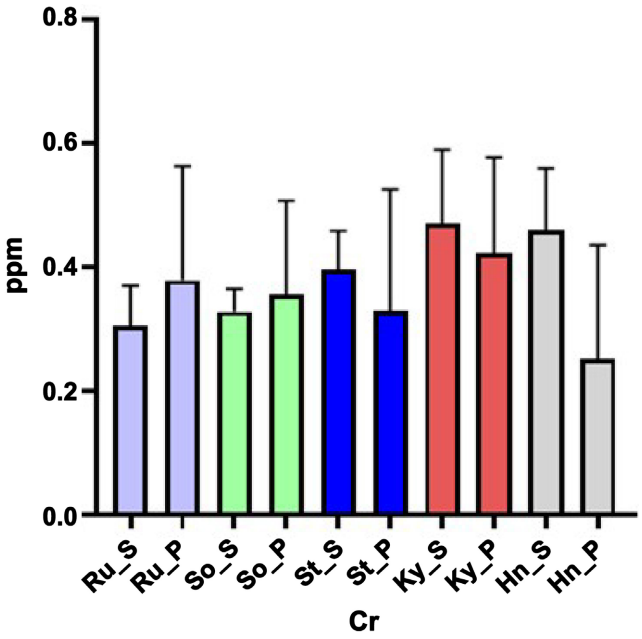

Figure 4. Mean Cr concentrations in water expressed in mg/L.

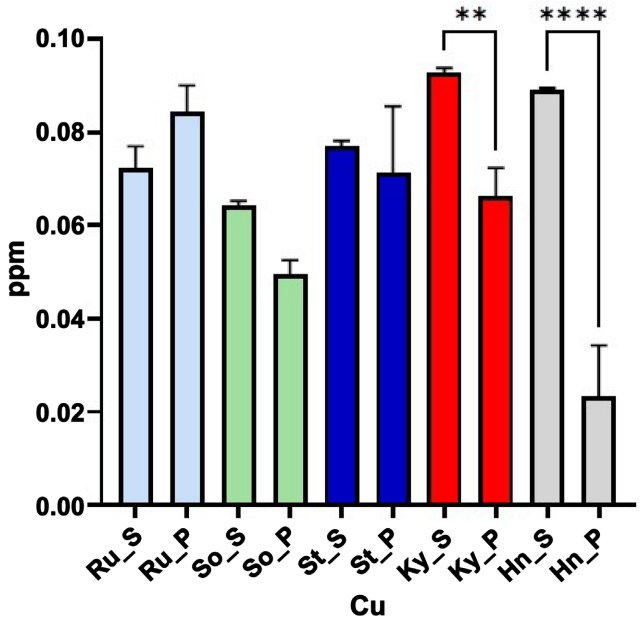

Figure 5. Mean Cu concentrations in water expressed in mg/L.

Figure 6 illustrates Fe concentrations in water ranging from 0.24 to 0.76 mg/L. The highest concentration recorded at Ru during the dry season exceeds the levels reported in surface waters of the Red Sea in Egypt during summer and spring [42], as well as tose in seawater from the Agadir coast in Morocco [41]. The Fe concentrations found in this study are also above the permissible limit set by the USEPA

[39]. Only the So and Hn sites showed statistically significant seasonal variability ($p < 0.05$).

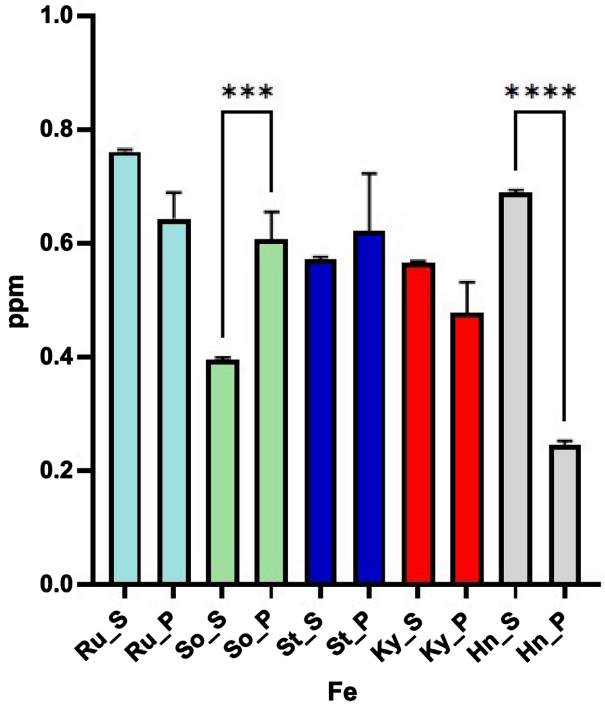

Figure 6. Mean Fe content in water expressed in mg/L.

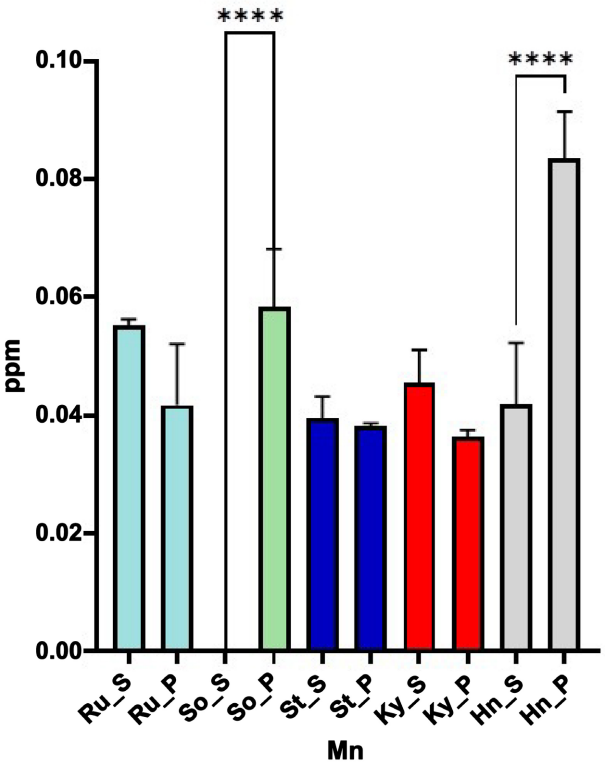

Figure 7. Average Mn concentrations in water expressed in mg/L.

The highest Mn concentration (0.08 mg/L) recorded during the wet season at the Hn site (**Figure 7**) is higher than the results obtained by Diop *et al.*, who found 12.13 µg/L in the water column off the coast of Dakar [13] and those reported by Ahmed *et al.*, who found values ranging from 0.21 - 0.39 µg/L in summer, 0.06 - 0.24 µg/L in autumn, 0.10 - 0.28 µg/L in winter, and 0.14 - 0.30 µg/L in spring in the surface waters of the Red Sea in Egypt [42]. The Mn values found in this study remain below the tolerable limit set by the USEPA [39].

3.3. Seasonal Variation in the Level of Heavy Metals Contamination in Sediments

The concentrations of heavy metals in sediments are presented in **Table 3**. The mean heavy metals values followed a similar trend across both seasons: Fe > Pb > Mn > Cr > Cu > Cd. Except for Fe, whose highest average concentration (Fe: 442.38 mg/kg) was recorded during the wet season, the highest levels of all other elements were observed in the dry season. The lower heavy metals concentrations in the wet season could be attributed to dilution effect, not only from input of less contaminated sediments but also due to mechanisms involved in the solid/liquid distribution of metal cations [44]. Additionally, metals accumulated in sediments may be resuspended due to natural phenomena (tides, storms) or anthropogenic activities (dredging) [45]. Thus, sediments may serve a potential source of metals through remobilization, even after the cessation of industrial activities, which can result in higher remobilization rates and, consequently, increased bioavailability of heavy metals in sediments and water [46] [47]. Van Den Berg *et al.*, in a natural environment study, demonstrated that dredged sludge discharge increases total metal content in the water column, although dissolved metal concentrations remain unaffected [48].

The highest concentrations of Cd and Cr concentrations recorded in this study exceed those found in surface sediments from the Saint-Louis estuary in Senegal by Diop *et al.* [14], whereas Pb, Cu, and Mn concentrations are lower (**Table 3**). The Pb, Cd, Cr, and Cu values were also higher than those reported by Tunde *et al.* [49] in sediments from Odonto Coastal in Nigeria and by Nour *et al.* [50] in the sediments of Suez Bay (Egypt). While the average concentrations of Pb, Cu, and Cr in the marine sediments from the Dakar Peninsula were higher than those found in the present study [17], the Cd concentrations measured were lower than those reported by Ahmed *et al.* in summer and fall [42]. A limitation of this work is its restricted geographic scope, as only five sites along the Senegalese coastline were investigated; while these locations were selected to represent major anthropogenic pressures, the results may not fully reflect the broader regional contamination context.

The heavy metals concentrations recorded in this study were also compared to the sediment quality guidelines threshold effect (TEL) and probable effect (PEL). These criteria are used to determine the potential risk associated with heavy metals present in the analyzed sediments. Generally, heavy metals concentrations between TEL and PEL values, as well as those above the PEL, represent the range

where adverse biological effects are likely to occur frequently; whereas heavy metals concentrations below the TEL indicate that harmful biological effects are unlikely to occur [51]. Overall, the highest mean concentrations in this study are below the TEL and PEL guidelines, except for Cd, which exceeds the TEL at all sites in both seasons except Ky, and for Pb at the So and Ru sites. Additionally, the Cd concentration (3.75 mg/kg) at the So site during the dry season exceeds the PEL standard values (**Table 3**). The presence of cadmium in concentration exceeding aquatic life protection criteria at the So site may attributed to domestic wastewater discharges from Canal 4. This bay indeed receives untreated domestic wastewater from hospitals and residential areas across a large part of the city of Dakar [16] [52].

Table 3. Seasonal variation of Pb, Cd, Cu, Fe, Mn, and Cr (mg/kg) in sediment samples collected from the coast of Dakar and the Saint Louis estuary.

Site	Ru		So		St		Hn		Ky		TEL	PEL
Season / HMs	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry		
Pb	31.20 ± 2.83^b	44.51 ± 4.50^a	41.90 ± 2.7^a	28.39 ± 6.42^b	20.92 ± 10.61^b	22.89 ± 2.33^a	19.08 ± 8.11^a	26.78 ± 0.52^a	21.31 ± 4.96^a	21.78 ± 4.37^a	35	91.3
Cd	2.26 ± 0.01^a	3.15 ± 0.02^a	2.48 ± 0.62^a	3.75 ± 0.02^a	2.32 ± 0.15^a	2.51 ± 0.08^b	1.66 ± 0.06^b	1.58 ± 0.68^a	0.29 ± 0.06^a	0.77 ± 0.29^a	0.60	3.53
Cu	2.68 ± 0.55^b	4.61 ± 0.38^b	14.33 ± 0.14^a	16.31 ± 1.92^a	1.24 ± 0.43^a	0.24 ± 0.10^a	1.98 ± 0.78^b	4.93 ± 1.25^a	1.73 ± 0.38^a	1.50 ± 0.44^a	35.7	197
Fe	199.60 ± 1.37^a	362.78 ± 8.61^a	442.38 ± 2.35^a	302.46 ± 2.43^a	75.35 ± 1.49^a	65.74 ± 1.03^a	84.02 ± 1.17^a	185.08 ± 2.45^a	101.30 ± 1.15^a	137.79 ± 1.61^a	-	-
Mn	19.08 ± 0.42^a	27.65 ± 0.28^a	25.99 ± 0.07^a	21.69 ± 0.30^a	4.74 ± 0.43^a	3.55 ± 0.05^a	5.47 ± 0.47^a	8.93 ± 0.77^a	7.14 ± 0.31^b	7.58 ± 0.34^a	-	-
Cr	14.54 ± 0.22^a	13.11 ± 0.22^b	10.26 ± 0.22^a	16.55 ± 0.65^a	6.06 ± 0.37^a	13.20 ± 0.20^a	6.57 ± 0.10^b	8.98 ± 0.62^a	2.15 ± 0.05^a	2.48 ± 0.03^a	37.3	90

a and b indicate that the seasonal variation is significant at $p < 0.05$. Within rows, items with the same letters are not significantly different $p > 0.05$.

3.4. Pollution Assessment and Associated Risks

3.4.1. Enrichment Factor (EF) and Geo-Accumulation Index (Igeo)

The determination of Enrichment Factor (EF) and Geo-accumulation Index (Igeo) helped assess the degree of metal pollution in the sediments. EF and Igeo values for heavy metals across the studied sites during both seasons are listed in **Table 4**. EF values for Pb across all sites indicate substantial enrichment regardless of the season. For both seasons, the St site was found to be extremely enriched with Pb and severely enriched with Cd. Similarly, Hn was extremely enriched with Pb and severely enriched with Cd during the wet season. Cr exhibited a similar level of enrichment in all seasons. According to Diop *et al.*, an EF between 0.05 and 1.5 indicates that the metal is entirely of geogenic origin, whereas an EF above 1.5 suggests an anthropogenic origin [53]. In the present study, the average EF values for Pb exceed 1.5, suggesting an anthropogenic origin in the sediment [54]-[56]. Across all sites, EF values for Cu, Mn, and Fe indicate a deficiency or only minor enrichment.

The Igeo values for Pb range from 1.84 (Ky) to 2.89 (Ru) during the dry season. The lowest Igeo value during the wet season was recorded at Ky and the highest at So, with respective values of 1.54 and 2.80. These correspond to sediment class 3 "moderately to heavily polluted" and class 4 "heavily polluted" according to Muller's classification (**Table 4**).

Table 4. Enrichment factor (EF) and geoaccumulation index (Igeo) calculated for heavy metals in sediments from the Dakar coast and the Saint Louis estuary during the dry and wet seasons.

Site	Season	Igeo						EF					
		Pb	Cd	Cu	Mn	Fe	Cr	Pb	Cd	Cu	Mn	Fe	Cr
Hn	Wet	1.88 ± 1.06	−4.66 ± 0.05	−4.49 ± 0.65	−2.99 ± 0.13	−3.75 ± 0.02	1.55 ± 0.02	60.00 ± 47.75	15.67 ± 0.43	0.64 ± 0.26	1.69 ± 0.12	1.00 ± 0.00	38.98 ± 0.55
	Dry	2.16 ± 0.03	0.07 ± 0.58	−3.12 ± 0.39	−2.29 ± 0.13	−2.61 ± 0.02	1.27 ± 0.10	27.33 ± 0.70	4.92 ± 4.07	0.72 ± 0.18	1.26 ± 0.09	1.00 ± 0.00	14.20 ± 0.19
Ky	Wet	1.54 ± 0.34	−7.17 ± 0.27	−4.63 ± 0.33	−2.61 ± 0.06	−3.48 ± 0.02	−0.07 ± 0.04	33.04 ± 8.17	2.31 ± 0.43	0.46 ± 0.11	1.84 ± 0.09	1.00 ± 0.00	10.83 ± 0.12
	Dry	1.84 ± 0.29	−0.66 ± 0.50	−4.85 ± 0.40	−2.52 ± 0.06	−3.04 ± 0.02	−0.52 ± 0.02	29.89 ± 6.27	18.21 ± 0.15	0.29 ± 0.09	1.43 ± 0.06	1.00 ± 0.00	5.77 ± 0.07
Ru	Wet	2.38 ± 0.13	0.67 ± 0.00	−3.98 ± 0.28	−1.19 ± 0.03	−2.50 ± 0.01	2.04 ± 0.02	29.52 ± 2.67	9.02 ± 0.03	0.36 ± 0.07	2.49 ± 0.07	1.00 ± 0.00	23.58 ± 0.16
	Dry	2.89 ± 0.14	1.15 ± 0.01	−3.19 ± 0.12	−0.65 ± 0.01	−1.64 ± 0.03	1.88 ± 0.02	23.21 ± 2.74	5.40 ± 0.05	0.34 ± 0.04	1.99 ± 0.03	1.00 ± 0.00	2.09 ± 0.05
St	Wet	1.67 ± 0.76	−4.18 ± 0.09	−5.15 ± 0.57	−3.20 ± 0.13	−3.91 ± 0.03	1.43 ± 0.09	52.48 ± 26.93	24.56 ± 2.03	0.44 ± 0.15	1.64 ± 0.15	1.00 ± 0.00	4.33 ± 0.08
	Dry	1.93 ± 0.14	0.82 ± 0.05	−7.19 ± 1.15	−3.62 ± 0.02	−4.11 ± 0.02	1.89 ± 0.02	65.78 ± 6.85	19.00 ± 7.94	0.14 ± 0.11	1.41 ± 0.02	1.00 ± 0.00	64.43 ± 1.01
So	Wet	2.80 ± 0.09	−4.11 ± 0.39	−1.55 ± 0.01	−0.74 ± 0.00	−1.36 ± 0.01	2.19 ± 0.03	17.89 ± 1.24	4.46 ± 1.11	0.87 ± 0.01	1.53 ± 0.01	1.00 ± 0.00	11.52 ± 0.06
	Dry	2.22 ± 0.35	1.40 ± 0.01	−1.37 ± 0.17	−1.00 ± 0.02	−1.90 ± 0.01	2.22 ± 0.06	17.73 ± 4.03	9.86 ± 0.04	1.45 ± 0.16	1.87 ± 0.01	1.00 ± 0.00	16.62 ± 0.13

3.4.2. Contamination Factor and Degree of Contamination

Contamination factor (CF) and contamination degree (C_{deg}) results presented in Table 5 show that in all seasons, except at Ky and St, Pb had a contamination factor exceeding 6, as did Cr at So and, only at Ru during the wet season. This reflects a very high level of sediment contamination. These results suggest that heavy metals (Pb and Cr) are linked to anthropogenic activities [57] such as the discharge of untreated domestic and/or industrial wastewater into aquatic environments [58], as well asatmospheric deposition (from fuel, waste incineration, etc.) [58]. The highest level of heavy metals contamination level in sediments was observed at the So site (19.45), followed by Ru (16.34) and St (13.22) during the dry season. In the wet season, contamination degrees were 17.45 and 15.10 at Ru and So respectively.

Table 5. Contamination factor (CF) and degree of contamination (C_{deg}) calculated for heavy metals in sediment samples from different sites along the Dakar coast river and the Saint Louis estuary.

Site	Season	CF						C_{deg}
		Pb	Cd	Cu	Mn	Fe	Cr	
Hn	Wet	6.69 ± 5.34	1.74 ± 0.06	0.07 ± 0.03	0.19 ± 0.02	0.11 ± 0.00	4.34 ± 0.00	**13.14 ± 5.33**
	Dry	6.70 ± 0.13	1.20 ± 0.98	0.18 ± 0.04	0.31 ± 0.03	0.25 ± 0.00	3.48 ± 0.00	**12.11 ± 0.96**
Ky	Wet	4.43 ± 1.09	0.31 ± 0.06	0.06 ± 0.01	0.25 ± 0.01	0.13 ± 0.00	1.45 ± 0.00	**5.19 ± 1.06**
	Dry	5.45 ± 1.09	3.32 ± 0.02	0.05 ± 0.02	0.26 ± 0.01	0.18 ± 0.00	1.05 ± 0.00	**10.33 ± 1.10**
Ru	Wet	7.81 ± 0.71	2.39 ± 0.01	0.10 ± 0.02	0.66 ± 0.01	0.26 ± 0.00	6.24 ± 0.00	**17.45 ± 0.69**
	Dry	11.14 ± 1.13	2.60 ± 0.09	0.16 ± 0.01	0.95 ± 0.01	0.48 ± 0.01	1.00 ± 0.00	**16.34 ± 1.07**
St	Wet	5.24 ± 2.65	2.45 ± 0.16	0.04 ± 0.02	0.16 ± 0.01	0.10 ± 0.00	0.43 ± 0.00	**7.99 ± 2.68**
	Dry	5.7 ± 0.58	1.66 ± 0.72	0.01 ± 0.01	0.12 ± 0.00	0.09 ± 0.00	5.61 ± 0.00	**13.22 ± 0.57**
So	Wet	10.49 ± 0.68	2.61 ± 0.65	0.51 ± 0.01	0.90 ± 0.00	0.59 ± 0.00	6.76 ± 0.00	**15.10 ± 0.82**
	Dry	7.11 ± 1.61	3.95 ± 0.02	0.58 ± 0.07	0.75 ± 0.01	0.40 ± 0.00	6.66 ± 0.00	**19.45 ± 1.64**

3.4.3. Ecological Risk Coefficient (E_r) and Potential Risk Index (IR)

The potential ecological risk index (RI) provides an understanding of the overall ecological risk of sediments by considering the contamination factor of each heavy metals, while the ecological risk coefficient (E_r) reflects the individual ecological risk posed by a given metal in sediments. Results both parameters are presented in Table 6. The mean E_r values for Cu, Fe, and Mn were all below 40 at every site during both seasons. These results indicate that these heavy metals (Cu, Fe, and Mn) pose a low potential ecological risk to aquatic organisms [19]. For Pb, two sites, Ru in the dry season and So in the wet season, presented a moderate risk levels [$40 < E_r < 80$]. For Cd, during the dry season, the highest E_r were observed at So (118.55) and Ru (99.74), corresponding to the considerable risk [$80 < E_r < 160$] categories. Cr, on the other hand, exhibited a high ecological risk factor [$160 < E_r < 320$] at the So site during the wet season, with an E_r value of 205.24.

According to the RI classification, during the wet season, except Ky, all sites were categorized as moderate risk sites [$150 < RI < 300$]. So had the highest RI value (273.32), followed by Hn (174.01), Ru (162.68), and St (159.95). The risk decreased considerably during the dry season, with only So (172.11) and Ru (168.76) remaining int the moderate risk category, while the other sites fell into the low-risk classification.

Table 6. E_r and RI calculated for heavy metals in sediment samples collected from various sites along the coast of Dakar and the Saint Louis estuary.

Site	Season	Potential ecologic risk coefficient						Potential ecologic risk index
		Pb	Cd	Cu	Mn	Fe	Cr	
Hn	Wet	33.45 ± 26.72	8.72 ± 0.32	0.07 ± 0.03	0.19 ± 0.02	0.22 ± 0.00	130.20 ± 0.00	172.85 ± 26.57
	Dry	33.52 ± 0.65	35.95 ± 29.26	0.88 ± 0.22	0.31 ± 0.03	0.25 ± 0.00	6.97 ± 0.00	77.87 ± 29.28
Ky	Wet	22.17 ± 5.45	1.55 ± 0.30	0.06 ± 0.01	0.25 ± 0.01	0.27 ± 0.00	43.60 ± 0.00	67.90 ± 5.34
	Dry	27.26 ± 5.47	99.74 ± 0.55	0.27 ± 0.08	0.26 ± 0.01	0.18 ± 0.00	2.11 ± 0.00	129.81 ± 5.54
Ru	Wet	39.05 ± 3.55	51.67 ± 34.39	0.37 ± 0.26	0.66 ± 0.01	0.35 ± 0.15	70.69 ± 0.83	162.78 ± 69.13
	Dry	55.71 ± 5.63	77.92 ± 2.63	0.82 ± 0.07	0.95 ± 0.01	0.48 ± 0.01	2.00 ± 0.00	137.89 ± 4.58
St	Wet	26.18 ± 13.27	12.25 ± 0.78	0.04 ± 0.02	0.16 ± 0.01	0.20 ± 0.00	12.96 ± 0.00	51.80 ± 13.40
	Dry	28.65 ± 2.92	49.85 ± 21.55	0.06 ± 0.05	0.12 ± 0.00	0.09 ± 0.00	11.22 ± 0.00	89.99 ± 19.86
So	Wet	52.43 ± 3.39	13.07 ± 3.24	0.51 ± 0.01	0.90 ± 0.00	1.17 ± 0.01	202.68 ± 0.00	270.77 ± 4.08
	Dry	35.54 ± 8.04	118.55 ± 0.74	2.92 ± 0.34	0.75 ± 0.01	0.40 ± 0.00	13.32 ± 0.00	171.47 ± 7.85

3.5. Correlation Tests

3.5.1. Spearman Correlation Analysis of Water and Sediments

Significant Spearman's correlation coefficients between heavy metals in water samples during the dry and the wet season are presented in Table 7. During the dry season, Spearman's correlation analysis shows a negative correlation between Cu and Pb, Cu and Cd, Cr and Pb, and a positive correlation between Cd and Pb, Fe and Mn, and Cr and Cu. In the wet season, Fe is significantly and positively correlated with Pb, Cd, Cu, and Cr, as well as Cr with Cu, and Cd with Pb. How-

ever, a negative correlation was observed between Mn and Cu.

Table 7. Spearman correlation test of water heavy metals in water samples during for both seasons.

Dry	Pb	Cd	Cu	Mn	Fe	Cr
Pb	1					
Cd	0.54*	1				
Cu	−0.88*	−0.6*	1			
Mn	0.1	−0.03	0.32	1		
Fe	0.22	−0.31	0.2	0.76*	1	
Cr	−0.66*	−0.41	0.65*	0.19	0.11	1
Wet	**Pb**	**Cd**	**Cu**	**Mn**	**Fe**	**Cr**
Pb	1					
Cd	0.91*	1				
Cu	0.27	0.16	1			
Mn	0.24	0.38	−0.64*	1		
Fe	0.59*	0.7*	0.73*	−0.2	1	
Cr	0.11	0.23	0.51*	−0.02	0.52*	1

*Strong correlation between variables.

Table 8. Spearman's correlation test for sediments from both seasons.

Dry	Pb	Cd	Cu	Fe	Mn	Cr
Pb	1					
Cd	0.4	1				
Cu	0.47	0.55*	1			
Fe	0.7*	0.59*	0.74*	1		
Mn	0.69*	0.59*	0.72*	0.98*	1	
Cr	0.22	0.88*	0.35	0.24	0.25	1
Wet	Pb	Cd	Cu	Fe	Mn	Cr
Pb	1					
Cd	0.46	1				
Cu	0.59*	0.36	1			
Fe	0.71*	0.22	0.75*	1		
Mn	0.81*	0.24	0.71*	0.95*	1	
Cr	0.56*	0.54*	0.63*	0.58*	0.58*	1

Table 8 presents Spearman's correlation analysis between six heavy metals in sediments during the dry and wet season. The results show positive correlations between Cu and Cd, Fe and Pb, Fe and Cd, Fe and Cu, and Cr and Cd in the dry season; and between Cu and Pb, Cr and Pb, Cr and Cd, Cr and Cu, Cr and Fe, and Cr and Mn in the wet season. No negative correlation was observed between the

different metals, regardless of the season considered. Spearman correlation analysis of heavy metals concentrations allows for a comprehensive assessment of the origins of the different heavy metals found in water and sediments. The existence of a positive correlation between certain metals in both seasons suggests contamination sources that generally anthropogenic sources of contamination at the different sites [14] [19]. Additionally, the aforementioned heavy metal appeared to have similar sources, natural, anthropogenic, or mixed.

3.5.2. Principal Component Analysis (PCA) of Water and Sediments

Principal component analysis (PCA) is the most commonly used multivariate statistical method in environmental studies. It is frequently applied to investigate potential pollution sources (natural or anthropogenic), as well as the characteristics of their elements [59]. The Spearman correlation matrix was used to identify the relationship between metals confirmed by the PCA results.

In water samples, 73.7% of the total data variance was explained by the first (dim 1) and second (dim 2) principal components. Dim 1 explained 41.5% of the cumulative variance and showed positive correlation with Fe, Cu, and Cr (**Figure 8**). Dim 2 explained 32.2% of the cumulative variance and showed positive correlations with Cd and Pb. The sites contributing most significantly to the construction of the main axis in the dry season were Hann (14%) and Kayar (7%), whereas Soumbédioune (32%) and Rufisque (23%) dominate. During the dry season, Soumbédioune was more polluted with Cd, and correspondingly low levels of Mn were noted there. Rufisque had elevated Pb levels; Kayar had a high Cr concentration, and Hann was rich in Cu.

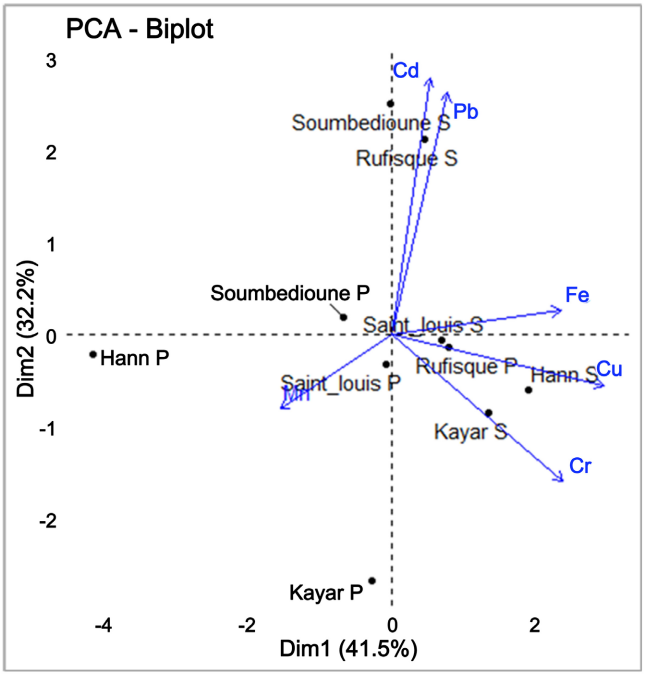

Figure 8. PCA showing the distribution of heavy metals between sites during the dry season (S) and wet season (P) of water samples.

In sediments, the first two axes (dim 1 and dim 2) explained 89% of the total variance in the data. Dim 1 explained 73.2% of the cumulative variance and showed positive correlations with Cu, Mn, Pb, and Fe. Dim 2 explained 15.8% of the cumulative variance and revealed positive correlations with Cr and Cd (Figure 9). The main sites contributing to the primary axis in the dry season were Soumbédioune and Rufisque (each 18%). For the second axis, the Saint-Louis site contributed most significantly with 28% in the dry season. Soumbédioune was polluted with Cd and Cr, whereas Rufisque showed higher levels of Pb, Fe, Mn, and Cu during the dry season.

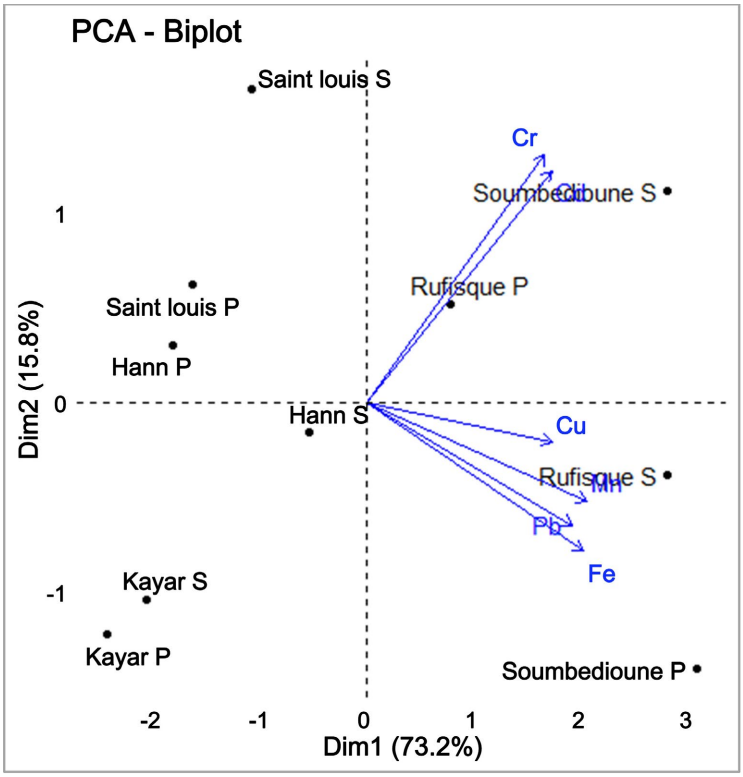

Figure 9. ACP showing the distribution of heavy metals between sites during the dry season (S) and wet season (P) of sediments.

4. Conclusion

Our study assessed the seasonal and spatial dynamics of Pb, Cd, Cu, Cr, Fe, and Mn in water and sediments along the Dakar coastline and at the Saint Louis estuary in Senegal. The results showed that the average concentrations of the different elements were generally higher during the dry season compared to the wet season. The study revealed that average dry season concentrations of Pb, Cd, Cr, and Fe in water exceeded the USEPA standard values, whereas in sediments, they remained below the sediment quality guideline limit TEL and PEL, except, for Cd at the Soumbédioune site. The sediment pollution assessment revealed moderate contamination levels in Pb, Cd, and Cr at the various sites. According to the ecological risk index, only the Soumbédioune and Rufisque sites presented moderate

risk levels associated with Cd and Pb, respectively. These findings highlight the need for regular monitoring of heavy metals pollution along the Senegalese coastline, with consideration of seasonality and element-specific contamination per site, in order to develop effective strategies to mitigate the potential harmful effects of pollution on aquatic life and public health.

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Conflicts of Interest

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

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