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Spatial Distribution and Contamination Level Assessment of Marine Sediment of the Safi Bay (Moroccan Atlantic Coast)

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Abstract: This study assesses the spatial distribution and contamination level of heavy metals in Safi Bay surface sediments. In this order, 28 surface sediment samples were retrieved from the study area and analyzed using the x-fluorescence method. To assess the contamination of the examined sediment, we used geo-ecological indices such as contamination factor (CF), degree of contamination (DC), geo accumulation index, and pollution load index (PLI). The results show that only Pb and Cd present moderate and considerable contamination in some sampling sites, while other elements (Cr, Cu, Zn, and Ni) indicate no contamination and low contamination by these elements. The inhomogeneous distribution of metal concentrations along the bay suggests different heavy metal sources. Given the ecological and socioeconomic importance of the study area, there is a need for a further analysis of both sediments and biological samples for a better understanding of the contamination levels and origin of metals, in addition to the sustainability of Safi Bay.

Keywords: heavy metals; sediment; spatial distribution; environmental indices; Safi Bay; Morocco

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1. Introduction

Heavy metals are common environmental pollutants in marine and coastal ecosystems because of their toxicity, non-biodegradability in sediments, and their bio-accumulative nature [1–8]. Once these pollutants reach aquatic environments from both natural processes and/or anthropogenic activities, they may damage marine organisms or can be accumulated in sediments via chemical adsorption and or physical precipitation [9–12], causing biodiversity loss [13,14]. In aquatic ecosystems, heavy metals do not remain for long in the water column but are precipitated and deposited in sediments as a final receptor [15]. Sediments represent an essential ecological component and play an important role in pollutant storage and distribution, which reflects actual system quality [7,16–19]. Accordingly, marine sediments can be used as an indicator of pollutants [20]. The growth of human activities around coastal cities, mainly industrial activities in response to the development of socioeconomic sectors, has resulted in human overpopulation and pollution level increase, affecting water resources, sediment, and marine organisms [8,11,21,22]. Indeed, coastal sediments have been found to be polluted by wastewater effluent issued from domestic and industrial activities [17,22–24], where several studies indicated that coastal sediment is an important tool for analyzing pollution levels by heavy metals [11,17,22,25–34]. According to statistical analysis, about 85% of heavy metals are accumulated in superficial sediments [11,22,35,36]. In this order, the study of the pollution level in a coastal environment, which provides various ecosystem services of environmental, socioeconomic, cultural, and recreational value [37], imposes analyzing sediment as an essential ecological component of the coastal environment.

The Bay of Safi is located on the Moroccan Atlantic coast, where multiple human activities are concentrated, including industrial activities, agriculture, and fishing, among others. Thus, the Bay of Safi is subjected to pollutants released from the growth of industrial activities along this littoral zone. Indeed, Kouali et al. and Rafiq et al. [38,39] have identified the intertidal area in Safi as a hotspot of metal contamination. However, few studies have been carried out to analyze the pollution level in this coastal zone despite its socioeconomic and ecological interests. Thus, this ongoing study is the first investigation of the degree of heavy metal pollution in the marine sediment of Safi Bay.

The main aims of this study are to:

- Analyze and quantify the pollution level by heavy metals in Safi Bay sediment using various environmental indices, including contamination factor (CF), degree of contamination (Cd), index of geo accumulation (Igeo), and pollution load index (PLI).
- Calculate the potential ecological risk of metals detected in the Safi Bay sediment.
- Establish the spatial distribution of heavy metals in Safi Bay.
- Attempt to define the possible origin of the heavy metals in this coastal environment to allow for the adequate and efficient management of Safi Bay for sustainable socioeconomic and environmental development.

2. Materials and Methods

2.1. Study Area

The Safi Bay is located on the Moroccan Atlantic coast (32°18′ N–9°15′ W) along a coastal line that extends about 5 km from the tip of the cliff of Sidi Bouzid in the north to Jorf Ammouni in the south (Figure 1). The study region includes the city beach with an NW-SE orientation and the sharp cliff south of the port with an N-S direction [40]. Safi Bay is a triangular bay which has experienced strong population growth and economic development in the last decade. It is characterized by chemical (phosphates) and parachemical industries (cement, brickworks, plateries) and the agro-industry, especially the fish canneries related to the fishing sector.

At the bottom of this bay, a port with industrial and mineral vocations has been established and is one of the main commercial ports in Morocco. This port has a general traffic of about 5 million tons, a major part of which is destined for mining exports. It is composed of three units (fishing port, commercial port, and ore carrier port). The commercial port has traffic of cereals, gypsum, barite, potash, manganese, fertilizers, and preserves, and the mineral port has traffic of phosphates, sulfur, and phosphoric acid; these industrial, urban, and port activities can constitute sources of heavy metals in this bay.

In Safi Bay, the slope of the continental shelf varies according to the depth, where it reaches 4% between the zero line and the isobath −10 m. The bottoms from −10 m to −25 m have only a slope between 2.5% and 1%. A vast plateau develops from −25 m to −30 m and gradually flares until it reaches a width of 2.5 km. The wave direction is dominant from NW to NNW [40], with the most frequent waves reaching 0.5 to 1.5 m [41]. The distribution of sediments at the bay is controlled by this swell, and an estimated transit of 250,000 m^3/year is generated [42].

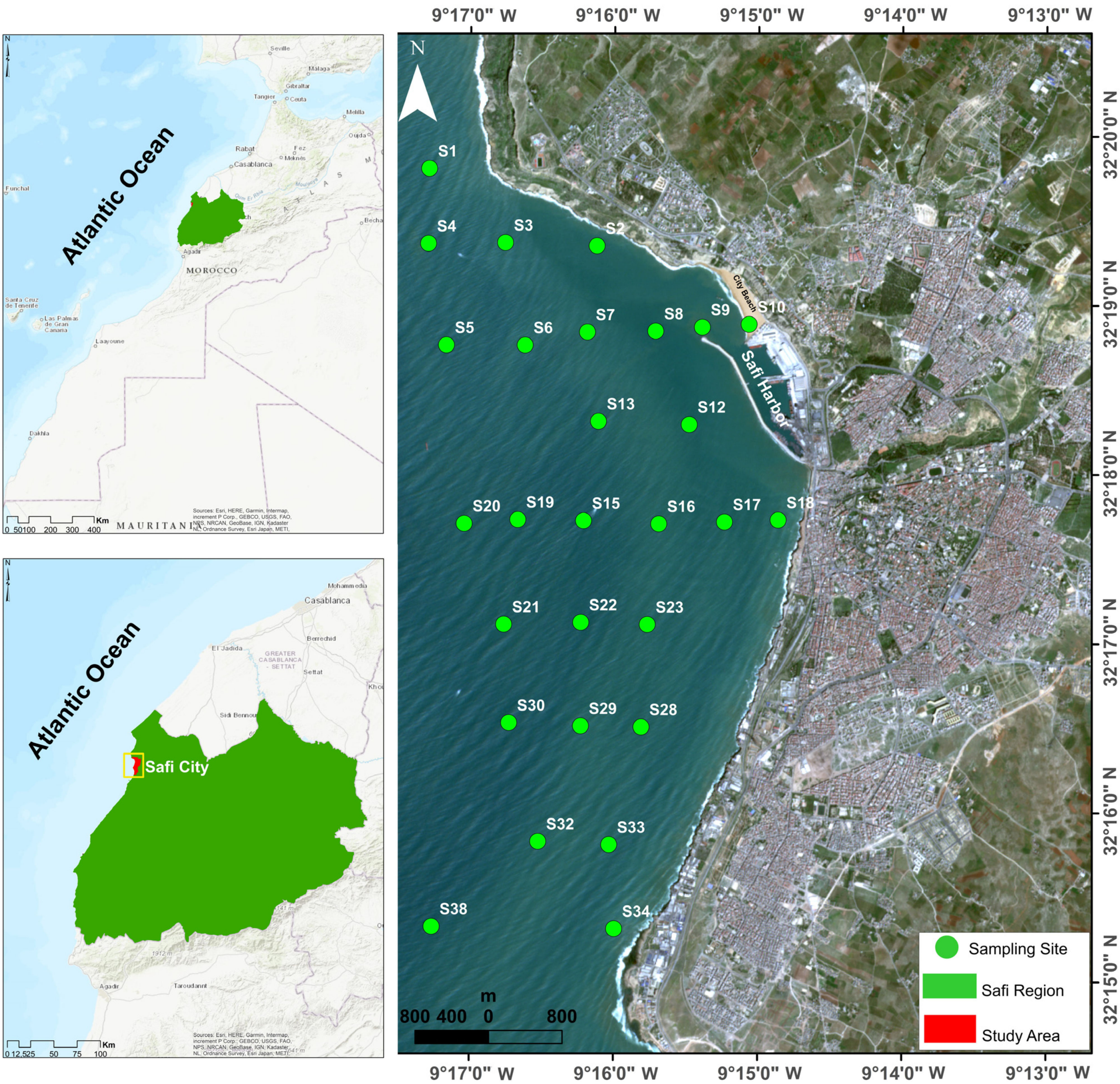

Figure 1. Study area and sampling locations, (S1, . . ., S38 are the sampling sites codes).

2.2. Sampling

The superficial sediments of the bay are composed of mostly bioclastic material, with significant biogenic sedimentation favored by the development of bedrock on which fixed organisms are abundant. In contrast, terrigenous detrital inputs are of little importance, while quartz grains and lutites are present only in sheltered coastal areas [43,44]. The main sedimentary inputs in the Bay of Safi come from the erosion of the north coast (cliffs) and are then transited by a north–south littoral drift [40–42]. This sediment distribution is controlled by natural (waves, currents) and anthropogenic (geomorphological modification by port developments) factors.

Twenty-eight sediment samples were retrieved in August 2019 on radials perpendicular to the coastline at different depths, with the water depth ranging from 3.5 m to 31.8 m (Figure 1 and Table 1). All samples were collected with a Van Veen grab, preserved in sealed polyethylene bags, and marked for particle size distribution determination, while only the fine fraction of the samples (sediment <63 μm) was considered for chemical composition analysis. These samples were dried at 50° in an oven and then sieved through 63 µm mesh size, crushed using the grinder, and placed in a new polyethylene bag.

Table 1. Sampling stations, depth (m), sand (%), mud (%), carbonate content, and textural class of each sample.

Stations	Latitude	Longitude	Depth (m)	Sand (%)	Mud (%)	%$CaCO_3$	Textural Class
S1	32°19′48.30″ N	9°17′17.10″ W	18.4	97.39	2.61	72.34	Sand
S2	32°19′21.05″ N	9°16′7.33″ W	6.5	98.79	1.21	82.13	Sand
S3	32°19′22.04″ N	9°16′45.43″ W	23.2	82.16	17.84	62.98	Slightly muddy sand
S4	32°19′21.54″ N	9°17′17.67″ W	30.08	97.16	2.84	78.30	Sand
S5	32°18′45.88″ N	9°17′10.03″ W	29.3	95.15	4.85	72.77	Sand
S6	32°18′49.35″ N	9°16′37.21″ W	25.5	92.02	7.98	71.06	Slightly muddy sand
S7	32°18′50.34″ N	9°16′11.42″ W	21.9	84.64	15.36	74.47	Slightly muddy sand
S8	32°18′50.83″ N	9°15′42.71″ W	17.05	96.86	3.14	79.57	Sand
S9	32°18′52.32″ N	9°15′23.37″ W	15.2	98.55	1.45	82.13	Sand
S10	32°18′53.31″ N	9°15′4.03″ W	3.5	98.86	1.14	82.55	Sand
S12	32°18′17.65″ N	9°15′28.64″ W	13.76	98.41	1.59	79.57	Sand
S13	32°18′18.64″ N	9°16′6.73″ W	23.5	95.88	4.12	79.57	Sand
S15	32°17′43.48″ N	9°16′12.58″ W	26.5	94.25	5.75	77.45	Sand
S16	32°17′42.49″ N	9°15′41.53″ W	25.8	95.41	4.59	77.87	Sand
S17	32°17′42.99″ N	9°15′14.00″ W	21.4	96.98	3.02	76.17	Sand
S18	32°17′43.97″ N	9°14′51.73″ W	12.5	96.94	3.06	69.36	Sand
S19	32°17′43.97″ N	9°16′40.12″ W	28.2	96.46	3.54	82.55	Sand
S20	32°17′42.48″ N	9°17′2.39″ W	29.74	93.72	6.28	65.53	Slightly muddy sand
S21	32°17′6.83″ N	9°16′45.97″ W	30.6	96.26	3.74	79.57	Sand
S22	32°17′7.33″ N	9°16′13.75″ W	28.4	93.85	6.15	73.62	Slightly muddy sand
S23	32°17′6.84″ N	9°15′46.21″ W	26.8	67.57	32.43	52.34	Muddy sand
S28	32°16′30.19″ N	9°15′48.56″ W	24.8	98.30	1.70	77.45	Sand
S29	32°16′30.68″ N	9°16′13.74″ W	26.5	87.41	12.59	37.02	Slightly muddy sand
S30	32°16′31.67″ N	9°16′43.62″ W	29.2	90.79	9.21	41.28	Slightly muddy sand
S32	32°15′49.57″ N	9°16′31.31″ W	26.3	97.35	2.65	80.00	Sand
S33	32°15′48.59″ N	9°16′2.03″ W	22.5	99.02	0.98	77.45	Sand
S34	32°15′18.87″ N	9°15′59.69″ W	11.22	96.96	3.04	72.34	Sand
S38	32°15′19.34″ N	9°17′15.84″ W	31.8	97.82	2.18	77.02	Sand

2.3. Heavy Metals Determination

Samples were prepared and analyzed at the Marine Geosciences and Soil Science Laboratory (LGMSS) to determine sediment texture and carbonate content using Bernard calcimetry (Table 1). The grain distribution of each sample was measured using a dry setting on a series of AFNOR standard sieves, and the granulometric parameters were calculated after classification according to [45].

For chemical analysis, only the fine fraction of samples <63 µm was analyzed, where 1 g of each sample was weighed, placed in a bag, and sent for analysis to the ICP-AES laboratory of the Centre National de Recherche Scientifique et Technique de Rabat (CNRST).

The first step of metals analysis consists of removing all organic matter from sediment, so approximately 1 g of dried samples and 10 mL of concentrated HNO_3 were placed together in a plastic digestion tube using a microwave digestion system. Then, a mixture of HNO_3-HFHCl was added to the sediment sample and heated to a temperature of 100–110 °C to obtain a transparent solution [46]. A total of 50 mL of demineralized water was added to the resulting solution and stored at room temperature for the subsequent analysis of heavy metals. The elements Cu, Zn, Cr, Ni, Pb, and Cd were determined, in the

Division of Technical Support Units for Scientific Research (UATRS) in the National Center for Scientific and Technical Research of Rabat (CNRST), using Jobin Yvon's ICP AES model Ultima 2 unit and controlled with 7.4 ICP-Expert Sequential software.

2.4. Statistical Analyses

ArcGis 10.8 software (Esri Co., Ltd., Redlands, CA, USA) was used to draw distribution maps of metal concentrations in surface sediments. All statistical analyses of the data (mean, minimum, maximum, Pearson correlation matrix, and contamination indices) were determined using XLSTAT statistical software 2019. Metal sources were analyzed using primary component analysis (PCA) and Pearson correlation analysis. The PCA was employed to examine both natural and man-made sources of potential pollution [47].

2.5. Assessment of the Environmental Pollution Degree

The environmental indices employed in this study have been widely used in studies related to pollution level assessment and quantification in coastal sediments [18,34,48–50]. Some authors have adopted many calculation methods [51–55], whose proposed pollution impact ranges to convert the measured concentrations of heavy metals in soil and sediment into a comprehensive description of pollution levels based on the intensity increase. Thus, in the present study, we used heavy metals pollution indices such as CF, DC, PLI, Igeo, and the potential ecological risk index (E_r^i and RI) to assess the pollution degree of Safi Bay sediments.

2.5.1. Contamination Factor (CF)

The contamination factor is an environmental indicator used to monitor and track the pollution level by heavy metals, where it allows for the assessment of the contamination degree by each metal in each sediment sample. CF values were obtained by dividing the concentration of each metal in the sediment by the baseline or background value (Equation (1)) [52].

$$\mathrm{CF} = \frac{\mathrm{C_{sample}}}{\mathrm{C_{background}}} \tag{1}$$

where $\mathrm{C_{sample}}$ is the concentration of metal measured in the studied samples, and $\mathrm{C_{background}}$ designates the metal concentration of the reference material or the background value. The authors in [52] defined four categories for sediment quality based on the CF calculated value ranging from low contamination (CF < 1), moderate contamination ($1 \leq$ CF < 3), considerable contamination ($3 \leq$ CF < 6), to very high contamination (CF ≥ 6).

2.5.2. Degree of Contamination (DC)

The degree of contamination (DC) is an index that can be derived from CF values and defined as the sum of all individual metal contamination factors [52]. It is calculated as follows (Equation (2)):

$$\mathrm{DC} = \sum_{i=1}^{9} \mathrm{Ci}\, f \tag{2}$$

As the utilized components for this index are not always possible to analyze, Abrahim et al. (2008) [56] proposed an alternative method. The modified equation proposed to calculate the degree of contamination is given below (Equation (3)):

$$\mathrm{mCd} = \sum_{i=1}^{9} \mathrm{Ci}\, f \tag{3}$$

Regarding the classification and description of the modified contamination degree of sediments, the following terminology was adopted (Table 2):

Table 2. Description of the modified contamination degree classification.

Classification	Description
0 < mCd < 1.5	Nil–very low degree of contamination
1.5 < mCd < 2	Low degree of contamination
2 < mCd < 4	Moderate degree of contamination
4 < mCd < 8	High degree of contamination
8 < mCd < 16	Very high degree of contamination
16 < mCd < 32	Extremely high degree of contamination
mCd ≥ 32	Ultra-high degree of contamination

2.5.3. Pollution Load Index (PLI)

The PLI is used as an indicator of contamination level by heavy metals for each sampling point [57,58]. The PLI is calculated through the following equation:

$$\mathrm{PLI} = (\mathrm{CF}_1 \times \mathrm{CF}_2 \times \mathrm{CF}_3 \times \ldots \times \mathrm{CF}_\mathrm{n})^{1/\mathrm{n}} \quad (4)$$

where "n" is the number of determined metals, and CF designates the contamination factor. The contamination can be estimated as follows:

PLI < 1, no metal pollution;
PLI > 1, polluted condition.

2.5.4. Geo-Accumulation Index (Igeo)

The Igeo was used to assess the metal pollution in the sediment of Safi Bay. The following equation is used to calculate the Igeo for each metal in each sample [51]:

$$\mathrm{Igeo} = \log 2\left(\frac{\mathrm{Cn}}{1.5\,\mathrm{Bn}}\right) \quad (5)$$

where Cn is the measured concentration of the heavy metal (n) in the investigated sediments, and Bn is the background value; here, we used the average abundance value of the upper continental crust (UCC) of a given metal. Also, 1.5 is the background matrix correction factor due to lithogenic effects [59–63]. The classification of sediment pollution level depends on the value of the Igeo, where 7 classes have been defined in Table 3.

Table 3. Geo-accumulation index classes and designation.

Igeo Value	Igeo Class	Designation of Sediment Quality
>5	6	Extremely contaminated
4–5	5	Strongly to extremely contaminated
3–4	4	Strongly contaminated
2–3	3	Moderately to strongly contaminated
1–2	2	Moderately contaminated
0–1	1	Uncontaminated to moderately contaminated
<0	0	Uncontaminated

2.5.5. Potential Ecological Risk Index (E_r^i and RI)

The potential ecological risk factor E_r^i and the potential ecological risk index (RI) were proposed by [52]. Those indices were widely used to evaluate the potential ecological risk associated with heavy metals in aquatic sediments [6,64–68].

E_r^i is calculated using the following equation [52]:

$$C_f^i = C^i / C_n^i \quad (6)$$

$$E_r^i = T_r^i \times C_f^i \quad (7)$$

$$RI = \sum_{i=1}^{n} E_r^i \quad (8)$$

where E_r^i is the potential ecological risk factor of each heavy metal, and T_r^i is the toxic response factor for heavy metal i. The toxic response factor for Cu, Zn, Cr, Ni, Pb, Cd, and V is 5, 1, 2, 5,5, 30, and 2, respectively [52,69,70], C_f^i is the contamination factor of heavy metal i, and C^i is the measured concentration of heavy metal i in the sediment. The E_r^i and RI values were deduced as follows [7,10,22,71,72]:

2.5.6. Sediment Quality Guidelines (SQGs)

Several authors [11–13,33,34] have assessed the impact of metals on the toxicity of aquatic organisms using sediment quality guidelines (SQGs). The threshold effect level (TEL) and probable effect level (PEL) were used in this study to assess the potential biotic influence of metals contained in sediment samples.

3. Results and Discussions

3.1. Spatial Distribution of Sediment Grain Size and $CaCO_3$ Content

The spatial distribution of sediment grain size and $CaCO_3$ content are shown in Figure 2. The collected samples are almost sandy except for S23, S7, and S3, which show a relatively important fine fraction of 32.42%. The sand fraction oscillates between 99% and 67.85%. The $CaCO_3$ content ranged from 37 to 82.5%, while its spatial distribution shows a similar trend as sand fraction, reflecting a significant correlation between sand and $CaCO_3$ content. The lowest values of $CaCO_3$ were recorded in the stations with a significant portion of mud, mainly S29, S30, and S23.

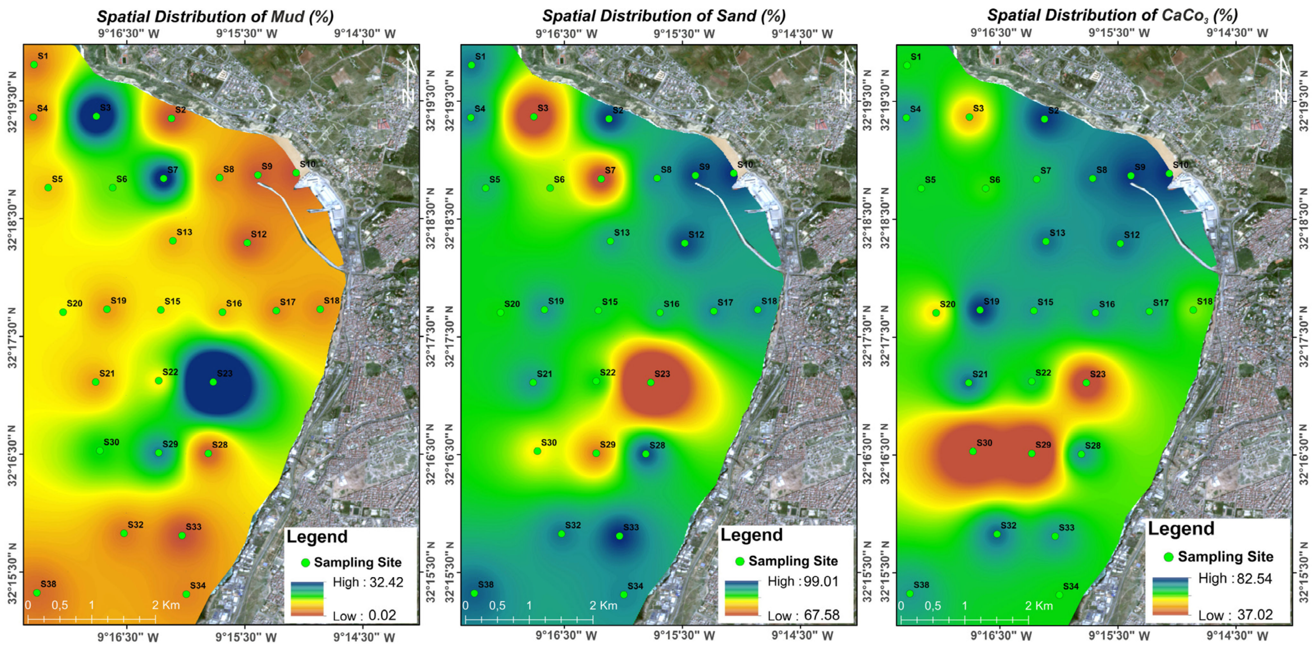

Figure 2. Spatial distribution map of sand, mud, and $CaCO_3$.

3.2. Assessment of the Surface Sediment Contamination by Heavy Metals

Twenty-eight sediment samples retrieved from Safi Bay have been analyzed for Cu, Zn, Cr, Ni, Pb, and Cd concentration determination. The concentrations fluctuate from one sampling point to another, probably reflecting different origins. The metals concentrations varied over the following ranges: Cd (0.305–0.801 mg/kg); Cr (0.305–120.983 mg/kg); Cu (1.740–12.715 mg/kg); Ni (1.573–81.319 mg/kg); Pb (16.575–63.381 mg/kg); and Zn

(14.266–127.719 mg/kg). The highest concentrations were recorded in the following stations: S15 (Ni), S17 (Zn), S23 (Cr et Pb), and S29 (Cd et Pb). Industrial and domestic discharges into the ocean are the possible origin of the highest values detected in these sediment samples as they are collected near the city. In addition, these domestic and industrial discharges flow directly into the ocean as the treatment plant is still an ongoing project. The lowest values were registered in the samples retrieved from the north part of the bay, distant from the city and related anthropogenic discharges. Noting also that natural factors such as the granulometric composition of the sediment, seawater dilution levels, and the hydrodynamic conditions that characterize the sampling sites can also affect the distribution of heavy metals in Safi Bay [73]. Noting that stations S23 and S29 indicate significant content fine fractions compared to other sites, explaining the highest recorded concentrations. It is well known that fine fractions accumulate pollutants more than coarser fractions because of their high specific surface area, whereas the presence of important pollutant concentrations in coarser fractions can be explained most likely by the coating phenomena. Organic matter coating on mineral particles may enhance the capacity of dissolved pollutants adsorption [74,75]. Moderate concentrations were found in the following stations, S5, S6, S7, S8, S9, and S10, located near the entrance of loading and unloading vessels for chemical and mining products in Safi port. Figure 3 displays the spatial distribution of heavy metals in Safi Bay, suggesting that the highest concentrations of heavy metals are associated mainly with human activities and port activities, which is in good accordance with the findings of [67], as the lowest concentrations were recorded in the north part far from the Safi port and anthropogenic discharges.

The average concentrations of heavy metals of all sampling stations for each metal Zn = 36.546 mg/kg, Pb = 33.972 mg/kg, Cr = 11.343 mg/kg, Ni = 10.395 mg/kg, Cu = 3.850 mg/kg, Cd = 0.395 mg/kg were compared to the average concentrations found in sediments from similar ecosystems in the world and to upper continental crust (UCC) values Table 4. The heavy metal concentrations of this study were almost less high than those reported in Dakhla Bay, except for Ni and Zn [76]. Cu, Zn, and Pb show low concentrations compared to almost all the coastal ecosystems listed in Table 5. The heavy metal concentrations were indeed compared to the sediment quality guideline values, including the threshold effect level (TEL) used to show the concentrations below, where no effect of metal content was detected in sediment on aquatic organisms and the toxic effect threshold (TET) utilized to indicate the heavy metals concentrations, above which substantial effects are likely to occur [77]. Heavy metal concentrations in Safi Bay sediments are less significant than the TELs values in Table 4; therefore, they do/did not present a toxicity risk to marine organisms living in these sediments.

Table 4. The E_r^i and RI values classification.

E_r^i Value	Risk Intensity	RI Value	Risk Intensity
<40	Low ecological risk	<150	Low ecological risk
$40 < E_r^i \leq 80$	Moderate ecological risk	$150 \leq RI < 300$	Moderate ecological risk
$80 < E_r^i \leq 160$	Appreciable ecological risk	$300 \leq RI < 600$	Considerable ecological risk
$160 < E_r^i \leq 320$	High ecological risk	RI > 600	Very high ecological risk
$E_r^i > 320$	Serious ecological risk		

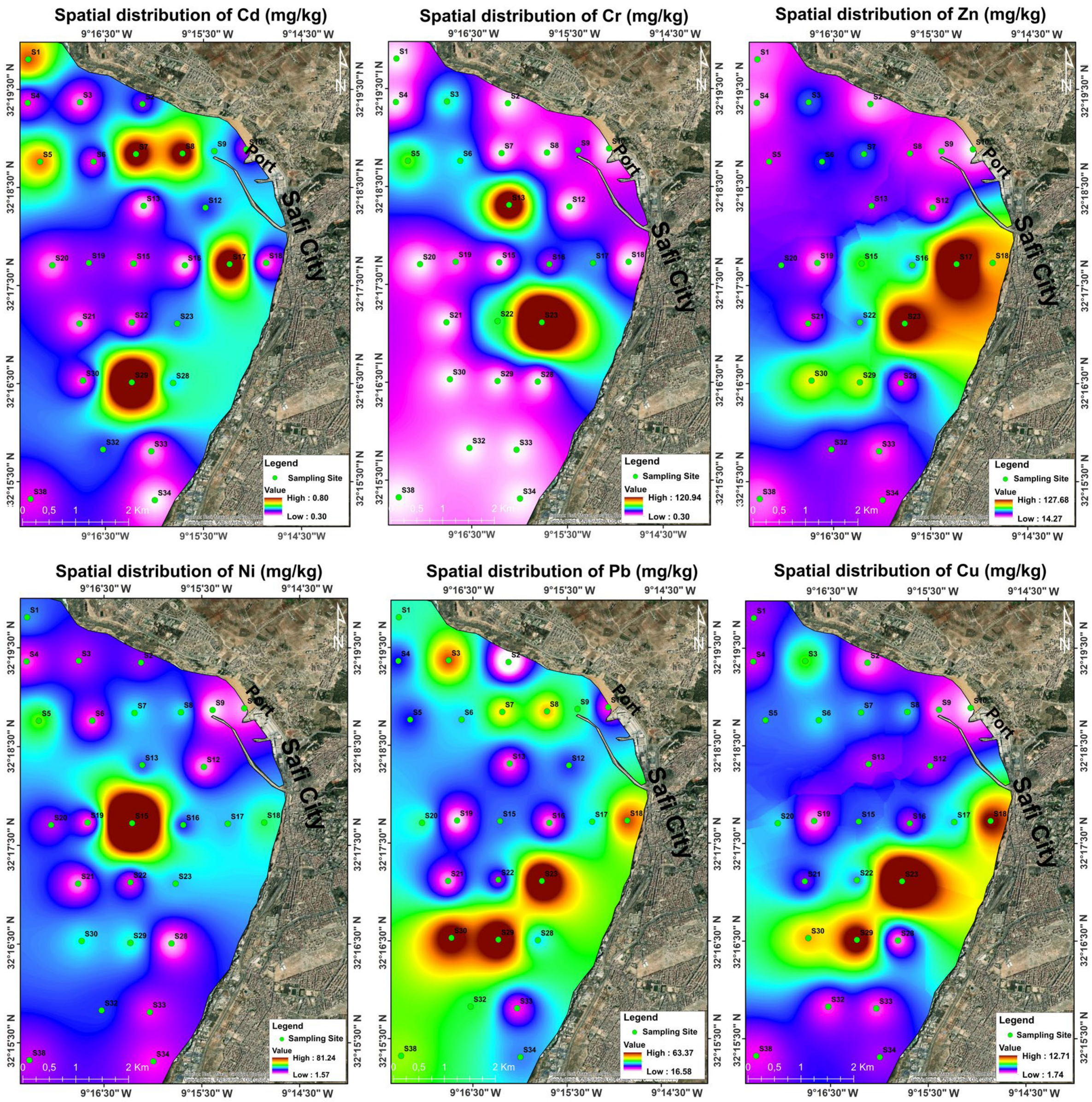

Figure 3. The spatial distribution map of Cd (mg/kg), Cr (mg/kg), Zn (mg/kg), Ni (mg/kg), Pb (mg/kg), and Cu (mg/kg) determined in the fine fractions of sediment samples.

Table 5. Comparison table of the heavy metal concentrations measured in Safi Bay surface sediment and other similar marine ecosystems. (ND: not determined).

Locations	Metal Concentrations (mg/kg)						References
	Cd	Cr	Cu	Ni	Pb	Zn	
Safi Bay, Morocco	0.395	11.343	3.850	10.395	33.972	36.546	Present study
Dakhla Bay, Morocco	0.4	108	17.3	5.8	71.3	20.8	[76]
Bohai Bay, China	0.04–0.84	ND	7.20–44.0	ND	5.90–97.0	56.3–309	[78]
Bay of Bengal, India	19.8	109.45	76.45	27.984	49.629	78.76	[8]
Zhelin Bay, China	0.063	23.07	7.95	7.5	35.69	74.95	[79]
Laizhou Bay, China	0.19	32.69	10.99	17.38	13.37	50.63	[11]
Tahaddart Estuary, Morocco	0.16	91.83	57.1	34.92	25.55	73.73	[66]

Table 5. *Cont.*

Locations	Metal Concentrations (mg/kg)						References
	Cd	Cr	Cu	Ni	Pb	Zn	
Oualidia Lagoon, Morocco	0.66	102.4	17.7	15.73	10.1	75.8	[18]
Nador Lagoon, Morocco	1.6	71.6	150.8	45.2	135	554.9	[10]
OumEr Bia estuary, Morocco	0.36	9.5	19.6	ND	28	138	[80]
The fishing port of Safi, Morocco	1.2–2.4	ND	45–90	ND	ND	276–552	[67]
Bay of Biscay, Spain	0.08–0.11	2.13–6.16	11.8–21.76	4.17–15.12	6.88–26.23	28.8–66.79	[81]
Upper Continental Crust	0.09	35	25	20	20	71	[82]
The suspended sediment of World Rivers	1.55	133	75.9	74.5	61.1	208	[83]
TEL	0.6	37.3	35.7	18	35	123	[84]
TET	3	100	86	61	170	540	[84]

3.3. Correlation among Metals

The Pearson correlation among the heavy metals results is shown in Table 5. The results indicate no significant correlation among heavy metals measured in Safi Bay sediment, suggesting a different origin of these metals in the bay in good accordance with their inhomogeneous distribution along the bay. Only Cu shows a highly significant correlation with Pb ($p < 0.01$), while Cu, Cr, and Zn indicate significant correlations ($p < 0.05$), which is in good accordance with Kouali et al.'s (2022) [38] findings. These significant correlations among Cu, Cr, and Zn may signify similar chemical properties, a similar degree of contamination, or derived from the same sources [85,86].

As shown in Table 6, a positive and significant correlation between Cr, Cu, and Pb with mud reveals the affinity of these metals to fine elements. The correlation matrix shows a negative and significant correlation observed for Cr, Cu, Pb, and Zn with $CaCO_3$ and sand, except for Cr and $CaCO_3$ (non-significant negative value), indicating that these metals are not associated with $CaCO_3$.

Table 6. Pearson correlation matrix of studied heavy metals, sand, mud, and $CaCO_3$ in Safi Bay.

Variables	Cd (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	Sand (%)	Mud (%)	%$CaCO_3$
Cd (mg/kg)	1.00								
Cr (mg/kg)	−0.07	1.00							
Cu (mg/kg)	0.27	0.62 *	1.00						
Ni (mg/kg)	0.05	−0.02	0.12	1.00					
Pb (mg/kg)	0.44	0.32	0.83 **	0.08	1.00				
Zn (mg/kg)	0.34	0.45	0.68 **	0.25	0.53 *	1.00			
Sand (%)	−0.18	−0.71 **	−0.82 **	−0.09	−0.70 **	−0.50	1.00		
Mud (%)	0.18	0.71 **	0.82 **	0.09	0.70 **	0.50	−1.00	1.00	
%$CaCO_3$	−0.35	−0.26	−0.78 **	−0.05	−0.81 **	−0.48	0.63 *	−0.63 *	1.00

Significant correlation marked (** $p < 0.01$) and (* $p < 0.05$).

The Dendrogamme (Figure 4) based on Ward's method [87] shows three different clusters: Cluster 1 (sand and $CaCO_3$), Cluster 2 (Pb and Zn), and Cluster 3 (Cr, Ni, Cd, Cu, and mud).

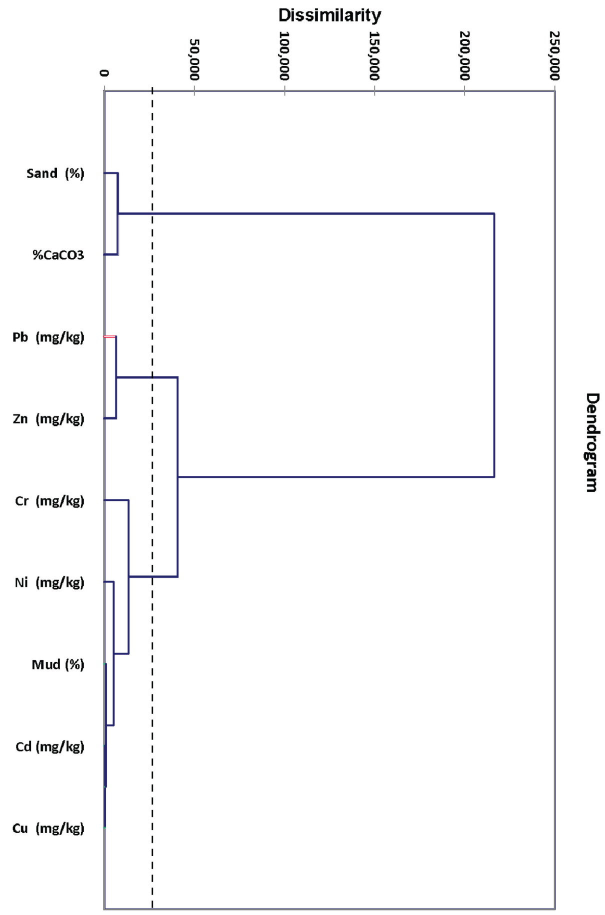

Figure 4. Dendrogram produced with the classification ascendant hierarchy (CAH) representing all variables.

3.4. Assessment of Heavy Metal Contamination

The results of the calculated indices CF, DC, mCd, and PLI for the sediment collected from Safi Bay are shown in Table 6. Except for S17 and S29, which show considerable contamination by Cd, almost all the stations display low to moderate contamination by Cd CF > 3. The contamination factor for Pb indicates considerable contamination in stations S3, S7, S8, S18, S23, S29, S30, and S38, suggesting an anthropogenic origin, while moderate contamination was recorded in the other sampling sites. Other investigated heavy metals show low contamination, suggesting that Cd and Pb mainly contaminate the study area, which is in good accordance with [38], where the Cd exhibited moderate contamination of coastal sediment from Jorf Lihoudi in Safi. Both cadmium and lead indicated a strong positive correlation and considerable contamination, reflecting similar sources into the sediment bay. In addition, the inhomogeneous distribution of contamination levels along the bay reflects different origins of heavy metals, such as domestic, industrial, and ship effluent. Industrial- and port-activities-related waste are reported as the main activities having heavy impacts on the bay environment [88]. The management of this ecosystem is a major concern as 70% of the released waste is thrown into the bay without pre-treatment [88]. In addition, the navigation activities may have potential impacts on this ecosystem environment by causing physical modifications of seabed substrate and habitats [89]. Ships were first identified as a major source of metal pollution in the 1970's, particularly copper [90].

A considerable degree of contamination was recorded in S23 and S29, while the other stations indicate low and moderate contamination in good accordance with the CF values.

The PLI values calculated for each station are shown in Table 7 and Figure 5. Almost all studied stations indicate no pollution by heavy metals, where the PLI values are inferior to 1. These results may be explained by the strong dilution and dispersion of heavy metal concentrations in seawater because of the strong agitation. The authors in [67] reported high PLI values for sediment retrieved inside the Safi harbor where the sediment grain size is finer, allowing for the accumulation of heavy metals. In contrast, almost all investigated samples were sandy with a high $CaCO_3$ content, suggesting that those factors are not controlling the distribution and accumulation of the heavy metals in Safi Bay sediments. Thus, further investigation of sediments mainly from the harbor area is needed to provide a clearer picture of the pollution levels and sources.

Table 7. Metal contamination factors (CFs), degree of contamination (DC), modified degree of contamination (mCd), and pollution load indices (PLIs) for sediments of all sites studied in Safi Bay.

Sites	Contamination Factor (Cf)						Degree of Contamination (DC)	Modified Degree of Contamination (mCd)	PLI
	Cd	Cr	Cu	Ni	Pb	Zn			
S1	2.53	0.00	0.05	0.14	2.70	0.29	5.72	0.95	0.19
S2	1.78	0.00	0.04	0.09	1.33	0.24	3.49	0.58	0.14
S3	1.62	0.21	0.09	0.08	3.73	0.51	6.23	1.04	0.41
S4	1.68	0.00	0.05	0.06	2.25	0.25	4.29	0.72	0.15
S5	2.49	0.27	0.07	0.22	2.26	0.36	5.66	0.94	0.45
S6	1.69	0.19	0.07	0.06	2.52	0.48	5.01	0.84	0.35
S7	2.90	0.00	0.07	0.16	3.32	0.51	6.97	1.16	0.25
S8	2.81	0.00	0.07	0.16	3.42	0.34	6.81	1.13	0.23
S9	1.97	0.09	0.04	0.02	2.83	0.29	5.24	0.87	0.22
S10	1.74	0.00	0.03	0.04	1.91	0.20	3.93	0.65	0.12
S12	1.86	0.00	0.05	0.04	2.30	0.30	4.56	0.76	0.15
S13	1.55	0.61	0.05	0.13	1.81	0.39	4.54	0.76	0.40
S15	1.67	0.00	0.06	1.08	2.39	0.75	5.95	0.99	0.30
S16	1.54	0.09	0.05	0.12	1.78	0.56	4.13	0.69	0.30
S17	**3.04**	0.16	0.07	0.15	2.58	**1.82**	**7.83**	**1.30**	0.54
S18	1.63	0.00	0.14	0.19	3.74	0.93	6.62	1.10	0.28
S19	1.76	0.04	0.04	0.05	1.60	0.26	3.75	0.63	0.20
S20	1.61	0.00	0.07	0.09	2.73	0.44	4.94	0.82	0.18
S21	1.61	0.00	0.06	0.05	1.74	0.33	3.79	0.63	0.14
S22	1.64	0.24	0.07	0.07	2.08	0.53	4.62	0.77	0.36
S23	1.93	**1.21**	0.23	0.15	**5.07**	1.43	**10.01**	**1.67**	**0.92**
S28	1.98	0.00	0.04	0.03	2.57	0.33	4.95	0.83	0.14
S29	**4.01**	0.01	0.15	0.17	**4.89**	0.85	**10.08**	**1.68**	0.36
S30	1.65	0.00	0.11	0.16	4.28	0.86	7.07	1.18	0.27
S32	1.87	0.00	0.04	0.12	2.88	0.40	5.31	0.88	0.19
S33	1.59	0.00	0.04	0.07	1.89	0.31	3.91	0.65	0.14
S34	1.53	0.00	0.05	0.07	2.42	0.35	4.42	0.74	0.15
S38	1.70	0.00	0.05	0.08	3.08	0.29	5.20	0.87	0.16
Mean	1.97	0.11	0.07	0.14	2.72	0.52	5.54	0.92	0.27
Min	1.53	0.00	0.03	0.02	1.33	0.20	3.49	0.58	0.12
Max	4.01	1.21	0.23	1.08	5.07	1.82	10.08	1.68	0.92

Bold values represent significant contamination.

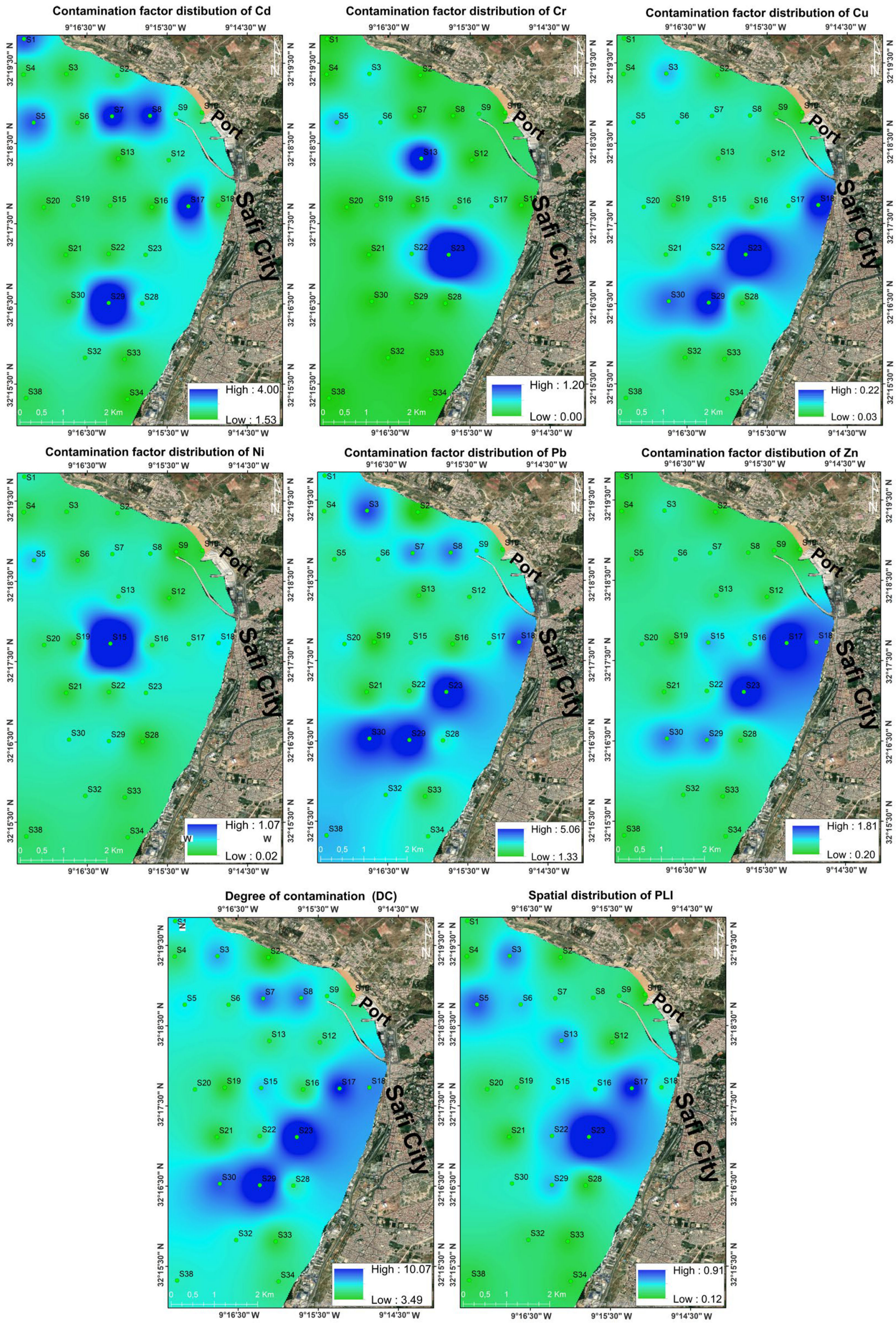

Figure 5. Spatial distribution map of CF, CD, and PLI.

The geo-accumulation index (Igeo)-calculated values for the investigated sediment are shown in Table 8. Almost all sampling sites show no pollution by Cr, Cu, Ni, and Zn. Only Cd and Pb show values that fluctuate between 0 and 2, indicating weak and moderate pollution, which is in good accordance with other calculated indices.

Table 8. Geo-accumulation index (Igeo) for metals in Safi Bay.

Sites	Geo-Accumulation Index (Igeo)					
	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
S1	0.75	−8.80	−4.85	−3.40	0.85	−2.37
S2	0.25	−8.72	−5.27	−4.02	−0.18	−2.62
S3	0.11	−2.86	−4.04	−4.23	1.31	−1.56
S4	0.16	−8.81	−4.94	−4.64	0.59	−2.56
S5	0.73	−2.50	−4.50	−2.76	0.59	−2.05
S6	0.17	−2.95	−4.35	−4.68	0.75	−1.65
S7	0.95	−8.60	−4.42	−3.19	1.15	−1.55
S8	0.90	−8.65	−4.39	−3.21	1.19	−2.12
S9	0.39	−4.08	−5.25	−6.16	0.92	−2.36
S10	0.21	−8.75	−5.57	−5.25	0.35	−2.88
S12	0.31	−8.66	−4.89	−5.08	0.61	−2.30
S13	0.04	−1.29	−4.89	−3.53	0.27	−1.95
S15	0.15	−8.82	−4.56	−0.47	0.67	−1.00
S16	0.04	−4.12	−4.90	−3.66	0.25	−1.43
S17	1.02	−3.19	−4.38	−3.32	0.78	0.28
S18	0.12	−8.85	−3.46	−2.96	1.32	−0.69
S19	0.23	−5.09	−5.29	−4.80	0.09	−2.52
S20	0.10	−8.86	−4.36	−4.13	0.86	−1.77
S21	0.10	−8.86	−4.75	−5.05	0.22	−2.17
S22	0.12	−2.64	−4.45	−4.43	0.47	−1.51
S23	0.36	−0.31	−2.70	−3.31	**1.76**	−0.07
S28	0.40	−8.57	−5.24	−5.57	0.77	−2.18
S29	**1.42**	−8.13	−3.32	−3.10	**1.71**	−0.82
S30	0.13	−8.83	−3.76	−3.19	1.51	−0.80
S32	0.31	−8.65	−5.09	−3.62	0.94	−1.92
S33	0.08	−8.88	−5.11	−4.38	0.34	−2.29
S34	0.02	−8.94	−4.83	−4.48	0.69	−2.12
S38	0.18	−8.79	−5.02	−4.20	1.04	−2.37
Mean	0.35	−6.65	−4.59	−3.96	0.78	−1.76
Max	1.42	−0.31	−2.70	−0.47	1.76	0.28
Min	0.02	−8.94	−5.57	−6.16	−0.18	−2.88

Bold values represent significant contamination.

The ecological risk index E_r^i was used to assess the risk associated with heavy metal pollution in Safi Bay. The results of E_r^i calculation are presented in Table 9. The values of E_r^i ranged from 30.50 to 80.10 for Cd, with an average of 39.49; from 0.01 to 2.69 for Cr, with an average of 0.25; from 0.19 to 1.41 for Cu, with an average of 0.43; from 0.12 to 5.98 for Ni, with an average of 0.76; from 4.14 to 15.85 for Pb, with an average of 8.49; and from 0.18 to 1.34 for Zn, with an average of 0.38. The ecological risk index E_r^i of the investigated heavy metals was less than 40, reflecting a low ecological risk.

Table 9. Potential ecological risk factors (E_r^i) and potential ecological risk index (RI) for studied metals in Safi Bay.

Sites	Ecological Risk Factor (E_r^i)						RI	RI Grade
	Cd	Cr	Cu	Ni	Pb	Zn		
S1	50.60	0.01	0.32	0.78	8.44	0.21	60.36	Low
S2	35.60	0.01	0.24	0.51	4.14	0.18	40.68	Low
S3	32.30	0.46	0.56	0.44	11.64	0.38	45.77	Low
S4	33.50	0.01	0.30	0.33	7.04	0.19	41.36	Low
S5	49.80	0.59	0.41	1.22	7.05	0.27	59.33	Low
S6	33.70	0.43	0.45	0.32	7.88	0.35	43.14	Low
S7	57.90	0.01	0.43	0.91	10.38	0.38	70.00	Low
S8	56.10	0.01	0.44	0.89	10.70	0.25	68.39	Low
S9	39.30	0.20	0.24	0.12	8.85	0.22	48.92	Low
S10	34.80	0.01	0.19	0.22	5.96	0.15	41.33	Low
S12	37.10	0.01	0.31	0.25	7.18	0.22	45.07	Low
S13	30.90	1.36	0.31	0.71	5.67	0.29	39.24	Low
S15	33.30	0.01	0.39	5.98	7.46	0.55	47.69	Low
S16	30.80	0.19	0.31	0.66	5.57	0.41	37.94	Low
S17	60.80	0.36	0.44	0.83	8.06	1.34	71.83	Low
S18	32.50	0.01	0.83	1.06	11.67	0.68	46.76	Low
S19	35.10	0.10	0.23	0.30	5.00	0.19	40.93	Low
S20	32.20	0.01	0.45	0.47	8.52	0.32	41.97	Low
S21	32.20	0.01	0.34	0.25	5.44	0.25	38.48	Low
S22	32.70	0.53	0.42	0.39	6.50	0.39	40.93	Low
S23	38.50	2.69	1.41	0.84	15.85	1.05	60.33	Low
S28	39.60	0.01	0.24	0.17	8.02	0.24	48.29	Low
S29	80.10	0.01	0.92	0.96	15.29	0.62	97.91	Low
S30	32.90	0.01	0.68	0.91	13.38	0.64	48.51	Low
S32	37.30	0.01	0.27	0.67	9.00	0.29	47.54	Low
S33	31.80	0.01	0.26	0.40	5.92	0.23	38.61	Low
S34	30.50	0.01	0.32	0.37	7.57	0.25	39.03	Low
S38	33.90	0.01	0.28	0.45	9.63	0.21	44.48	Low
Mean	39.49	0.25	0.43	0.76	8.49	0.38	49.81	Low
E_r^i grade	Low	Low	Low	Low	Low	Low	Low	

4. Conclusions

This study analyzed the spatial distribution of Cr, Zn, Cu, Ni, and Pb in Safi Bay sediments. The results showed an inhomogenous distribution of heavy metals along the bay, suggesting different sources of these metals. However, the concentrations of heavy metals were more elevated in the sampling sites located near the city and the Safi Port, while lower concentrations were recorded in the northern part of Safi City where human activities are less intense.

The use of environmental indices, including CF, DC, mCd, PLI, and E_r^i, allowed for the gathering of an understanding of the pollution levels of the bay sediments. The results revealed that the Safi Bay sediment is mainly contaminated by Cd and Pb according to the CF and DC factors. The PLI values were almost >1, suggesting that Safi Bay is an unpolluted area. However, the obtained results imply that there should be a further investigation of the bay sediments, mainly the sediment cores, which would allow for a better understanding of the pollution history in the study area to be obtained.

Factors such as the hydrodynamic conditions, currents, waves, and resuspension/deposition characterizing the study area need to be analyzed to obtain a better understanding of the pollutant spatial distribution and their concentration fluctuations sources.

This study is the first investigation of the contamination of Safi Bay sediments by heavy metals. Thus, the present work provides a database for future investigations of the bay's environmental quality, mainly its ecological and socioeconomic interests, contributing towards developing conservation and protection projects for the sustainable use of its related ecosystem services.

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References

1. Varol, M. Assessment of heavy metal contamination in sediments of the Tigris River (Turkey) using pollution indices and multivariate statistical techniques. *J. Hazard. Mater.* **2011**, *195*, 355–364. [CrossRef] [PubMed]
2. Haruna, A.; Uzairu, A.; Harrison, G. Chemical fractionation of trace metals in sewage water-irrigated soils. *Int. J. Environ. Res.* **2011**, *5*, 733–744.
3. Tam, N.; Wong, Y. Spatial variation of heavy metals in surface sediments of Hong Kong Mangrove Swamps. *Environ. Pollut.* **2000**, *110*, 195–205. [CrossRef] [PubMed]
4. Ghaderi, A.; Abduli, M.; Karbassi, A.; Nasrabadi, T.; Khajeh, M. Evaluating the effects of fertilizers on bioavailable metallic pollution of soils, case study of Sistan farms, Iran. *Int. J. Environ. Res.* **2012**, *6*, 565–570.
5. Gao, C.; Lin, Q.; Bao, K.; Zhao, H.; Zhang, Z.; Xing, W.; Wang, G. Historical variation and recent ecological risk of heavy metals in wetland sediments along Wusuli River, Northeast China. *Environ. Earth Sci.* **2014**, *72*, 4345–4355. [CrossRef]
6. Liu, J.; Yin, P.; Chen, B.; Gao, F.; Song, H.; Li, M. Distribution and contamination assessment of heavy metals in surface sediments of the Luanhe River Estuary, northwest of the Bohai Sea. *Mar. Pollut. Bull.* **2016**, *109*, 633–639. [CrossRef]
7. Malvandi, H. Preliminary evaluation of heavy metal contamination in the Zarrin-Gol River sediments, Iran. *Mar. Pollut. Bull.* **2017**, *117*, 547–553. [CrossRef]
8. Anbuselvan, N.; Senthil Nathan, D.; Sridharan, M. Heavy metal assessment in surface sediments off Coromandel Coast of India: Implication on marine pollution. *Mar. Pollut. Bull.* **2018**, *131*, 712–726. [CrossRef]
9. Priya, A.K.; Gnanasekaran, L.; Dutta, K.; Rajendran, S.; Balakrishnan, D.; Soto-Moscoso, M. Biosorption of heavy metals by microorganisms: Evaluation of different underlying mechanisms. *Chemosphere* **2022**, *307*, 135957. [CrossRef]
10. Maanan, M.M.; Saddik, M.; Chaibi, M.; Assobhei, O.; Zourarah, B. Environmental and ecological risk assessment of heavy metals in sediments of Nador lagoon, Morocco. *Ecol. Indic.* **2014**, *48*, 616–626. [CrossRef]
11. Zhang, Z.; Li, J.; Mamat, Z.; Ye, Q. Sources identification and pollution evaluation of heavy metals in the surface sediments of Bortala River. Northwest China. *Ecotoxicol. Environ. Saf.* **2015**, *126*, 94–101. [CrossRef] [PubMed]
12. Ali, M.M.; Ali, M.L.; Islam, M.S.; Rahman, M.Z. Preliminary assessment of heavy metals in water and sediment of Karnaphuli River, Bangladesh. *Environ. Nanotechnol. Monit. Manag.* **2016**, *5*, 27–35. [CrossRef]
13. Mejjad, N.; Laissaoui, A.; Fekri, A.; Benmhammed, A.; El Hammoumi, O.; Cherif, E.K. Does human activities growth lead to biodiversity loss in the Moroccan coastal lagoons? A diagnostic comparison study. In Proceedings of the 4th Edition of International Conference on Geo-IT and Water Resources 2020, Geo-IT and Water Resources 2020, Al-Hoceima, Morocco, 11–12 March 2020.
14. Yozukmaz, A.; Yabanlı, M. Heavy Metal Contamination and Potential Ecological Risk Assessment in Sediments of Lake Bafa (Turkey). *Sustainability* **2023**, *15*, 9969. [CrossRef]
15. Manav, R.; Uğur Görgün, A.; Filizok, I. Radionuclides (^{210}Po and ^{210}Pb) and some heavy metals in fish and sediments in Lake Bafa, Turkey, and the contribution of ^{210}Po to the radiation dose. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1113. [CrossRef] [PubMed]
16. Antizar-Ladislao, B.; Mondal, P.; Mitra, S.; Sarkar, S.K. Assessment of trace metal contamination level and toxicity in sediments from coastal regions of West Bengal, eastern part of India. *Mar. Pollut. Bull.* **2015**, *101*, 886–894. [CrossRef]

17. Qutu, J.; Junyu, H.; Guanqiong, Y.; George, C. Heavy metal contamination assessment of surface sediments of the East Zhejiang coastal area during 2012–2015. *Ecotoxicol. Environ. Saf.* **2018**, *163*, 444–455.
18. Mejjad, N.; Laissaoui, A.; El-Hammoumi, O.; Fekri, A.; Amsil, H.; El-Yahyaoui, A.; Benkdad, A. Geochemical, radiometric, and environmental approaches for the assessment of the intensity and chronology of metal contamination in the sediment cores from Oualidia lagoon (Morocco). *Environ. Sci. Pollut. Res.* **2018**, *25*, 22872–22888. [CrossRef]
19. Lin, L.; Li, C.; Yang, W.; Zhao, L.; Liu, M.; Li, Q.; Crittenden, J.C. Spatial variations and periodic changes in heavy metals in surface water and sediments of the Three Gorges Reservoir, China. *Chemosphere* **2020**, *240*, 124837. [CrossRef]
20. Hazem, T.A.; Talaat, A.H.; Ibrahim, M.S.; Khalid, M.E. Assessment of Heavy Metals Pollution in Marine Sediments along the Mediterranean Sea, Egypt. *J. Geogr. Environ. Earth Sci. Int.* **2016**, *7*, 1–11. [CrossRef]
21. Vidović, J.; Dolenec, M.; Dolenec, T.; Rožič, P.Ž. Benthic Foraminifera Assemblages as Elemental Pollution Bioindicator in Marine Sediments Around Fish Farm (Vrgada Island, Central Adriatic, Croatia). *Mar. Pollut. Bull.* **2014**, *83*, 198–213. [CrossRef]
22. Zhang, M.; He, P.; Qiao, G.; Huang, J.; Yuan, X.; Li, Q. Heavy metal contamination assessment of surface sediments of the Subei Shoal, China: Spatial distribution, source apportionment and ecological risk. *Chemosphere* **2019**, *223*, 211–222. [CrossRef] [PubMed]
23. Wang, X.S.; Qin, Y.; Sang, S.X. Accumulation and sources of heavy metals in urban topsoils: A case study from the city of Xuzhou, China. *Environ. Geol.* **2005**, *48*, 101–107. [CrossRef]
24. Bat, L.; Özkan, E.Y. Heavy metal levels in sediment of the Turkish Black Sea Coast. In *Oceanography and Coastal Informatics: Breakthroughs in Research and Practice*; Information Resources Management Association, Ed.; IGI Global: Hershey, PA, USA, 2019; pp. 86–107. [CrossRef]
25. Jayaprakash, M.; Jonathan, M.P.; Srinivasalu, S.; Muthuraj, S.; Ram-Mohan, V.; Rajeshwara-Rao, N. Acid-leachable trace metals in sediments from an industrialized region (Ennore Creek) of Chennai city, SE coast of India: An approach towards regular monitoring. *Estuary Coast. Shelf Sci.* **2008**, *76*, 692–703. [CrossRef]
26. Muthu Raj, S.; Jayaprakash, M. Distribution and enrichment of trace metals in marine sediments of Bay of Bengal, off Ennore. south-east coast of India. *Environ. Geol.* **2018**, *56*, 207–217. [CrossRef]
27. Gao, X.; Li, P. Concentration and fractionation of trace metals in surface sediments of intertidal Bohai Bay, China. *Mar. Pollut. Bull.* **2012**, *64*, 1529–1536. [CrossRef]
28. Pan, K.; Wang, W.X. Trace metal contamination in estuarine and coastal environments in China. *Sci. Total Environ.* **2012**, *421*, 3–16. [CrossRef]
29. Scheibye, K.; Weisser, J.; Borggaard, O.K.; Larsen, M.M.; Holm, P.E.; Vammen, K.; Christensen, J.H. Sediment baseline study of levels and sources of polycyclic aromatic hydrocarbons and heavy metals in Lake Nicaragua. *Chemosphere* **2014**, *95*, 556–565. [CrossRef]
30. Chen, H.; Chen, R.; Teng, Y.; Wu, J. Contamination characteristics, ecological risk and source identification of trace metals in sediments of the Le'an River (China). *Ecotoxicol. Environ. Saf.* **2016**, *125*, 85–92. [CrossRef]
31. Lu, J.; Li, A.; Huang, P. Distribution, sources and contamination assessment of heavy metals in surface sediments of the south yellow sea and northern part of the east China sea. *Mar. Pollut. Bull.* **2017**, *124*, 470–479. [CrossRef]
32. Liu, Q.; Wang, F.; Meng, F.; Jiang, L.; Li, G.; Zhou, R. Assessment of metal contamination in estuarine surface sediments from Dongying City, China: Use of a modified ecological risk index. *Mar. Pollut. Bull.* **2018**, *126*, 293–303. [CrossRef]
33. Benmhammed, A.; Laissaoui, A.; Mejjad, N.; Ziad, N.; Chakir, E.; Benkdad, A.; Bouh, H.A.; El Yahyaoui, A. Recent pollution records in Sidi Moussa coastal lagoon (western Morocco) inferred from sediment radiometric dating. *J. Environ. Radioact.* **2021**, *227*, 106464. [CrossRef]
34. Madadi, R.; Mejjad, N.; De-la-Torre, G.E. Geochemical speciation, ecological risk, and source identification of heavy metal(loid)s in sediments and waters from Musa Estuary, Persian Gulf. *Mar. Pollut. Bull.* **2023**, *190*, 114836. [CrossRef]
35. Zahra, A.; Hashmi, M.Z.; Malik, R.N.; Ahmed, Z. Enrichment and geoaccumulation of heavy metals and risk assessment of sediments of Kurang Nallah-feeding tributary of the Rawal Lake reservoir, Pakistan. *Sci. Total Environ.* **2014**, *470–471*, 925–933. [CrossRef]
36. Jiang, X.; Teng, A.; Xu, W.; Liu, X. Distribution and pollution assessment of heavy metals in surface sediments in the Yellow Sea. *Mar. Pollut. Bull.* **2014**, *83*, 366–375. [CrossRef]
37. Mejjad, N.; Rovere, M. Understanding the impacts of blue economy growth on deep-sea ecosystem services. *Sustainability* **2021**, *13*, 12478. [CrossRef]
38. Kouali, H.; Chaouti, A.; Achtak, H.; Elkalay, K.; Dahbi, A. Contamination and ecological risk assessment of trace metals in surface sediments from coastal areas (El Jadida, Safi and Essaouira) along the Atlantic coast of Morocco. *J. Afr. Earth Sci.* **2022**, *186*, 104417. [CrossRef]
39. Rafiq, F.; Techetach, M.; Achtak, H.; Boundir, Y.; Kouali, H.; Sisouane, M.; Mandri, B.; Cherifib, O.; Dahbi, A. First assessment of domestic and industrial effluents impact on intertidal zone of Safi coastline (west of Morocco): Physicochemical characteristics and metallic trace contamination. *Desalin. Water Treat.* **2022**, *245*, 167–177. [CrossRef]
40. Minoubi, A.; El Khalidi, K.; Chaibi, M.; Zourarah, B.; Ayt Ougougdal, M.; Poizot, E.; Mear, Y. Impact des ouvrages portuaires sur l'évolution du trait de côte de la baie de Safi (littoral atlantique-Maroc). *Rev. Marocaine Géomorphol.* **2018**, *2018*, 18–35.
41. Zakarya, E. La Houle et Son Impact sur le Littoral Atlantique Marocain, Approche par Modélisation. Ph.D. Thesis, Université de Paris IV, Paris, France, 1994.

42. Charrouf, L. Les Problèmes d'Ensablement des Ports Marocains sur la Façade Atlantique: Leur Impact Sédimentologique sur le Littoral. Ph.D. Thesis, Université de Paris-Sud, Centre Scientifique d'Orsay, Bures-sur-Yvette, France, 1989.
43. Cirac, P.; Faugeres, J.C.; Gayet, J. Résultats préliminaire d'une reconnaissance sédimentaire du plateau atlantique marocain. *Bull. l'Inst. Géol.* **1979**, *25*, 69–81.
44. Mathieu, R. Sédiments et Foraminifères Actuels de la Marge Continentale Atlantique du Maroc. Ph.D. Thesis, Université de Pierre et Marie Curie, Paris, France, 1986.
45. Folk, R.L.; Ward, W.C. A Study in the Significance of Grain-Size Parameters. *J. Sediment. Petrol.* **1957**, *27*, 3–26. [CrossRef]
46. Allen, S.E.; Grimshaw, H.M.; Rowland, A.P. Chemical analysis. In *Methods in Plant Ecology*; Moore, P.D., Chapman, S.B., Eds.; Blackwell Scientific Publication: Hoboken, NJ, USA, 1986; pp. 285–344.
47. Li, G.; Hu, B.; Bi, J.; Leng, Q.; Xiao, C.; Yang, Z. Heavy metals distribution and contamination in surface sediments of the coastal Shandong Peninsula (Yellow Sea). *Mar. Pollut. Bull.* **2013**, *76*, 420–426. [CrossRef] [PubMed]
48. Remeikaitė-Nikienė, N.; Garnaga-Budrė, G.; Lujanienė, G.; Jokšas, K.; Stankevičius, A.; Malejevas, V.; Barisevičiūtė, R. Distribution of metals and extent of contamination in sediments from the south-eastern Baltic Sea (Lithuanian zone). *Oceanologia* **2018**, *60*, 193–206. [CrossRef]
49. Elsagh, A.; Jalilian, H.; Aslshabestari, M.G. Evaluation of heavy metal pollution in coastal sediments of Bandar Abbas, the Persian Gulf, Iran: Mercury pollution and environmental geochemical indices. *Mar. Pollut. Bull.* **2021**, *167*, 112314. [CrossRef] [PubMed]
50. Ferreira, S.L.; da Silva Junior, J.B.; dos Santos, I.F.; de Oliveira, O.M.; Cerda, V.; Queiroz, A.F. Use of pollution indices and ecological risk in the assessment of contamination from chemical elements in soils and sediments–Practical aspects. *Trends Environ. Anal. Chem.* **2022**, *35*, e00169. [CrossRef]
51. Muller, G. Index of geoaccumulation in the sediments of the Rhine River. *GeoJournal* **1969**, *2*, 108–118.
52. Hokanson, L. Ecological risk index for aquatic pollution control, a sedimentological approach. *Water Res.* **1980**, *14*, 975–1001. [CrossRef]
53. Salomons, W.; Forstner, U. *Metals in the Hydrocycle*; eBook; Springer: Berlin/Heidelberg, Germany; Tokyo, Japan, 1984. [CrossRef]
54. Sakan, S.M.; Djordjevic, D.S.; Manojlovic, D.D.; Polic, P.S. Assessment of heavy metal pollutants accumulation in the Tisza river sediments. *J. Environ. Manag.* **2009**, *90*, 3382–3390. [CrossRef]
55. Sekabira, K.; Oryem Origa, H.; Basamba, T.; Mutumba, G.; Kakudidi, E. Assessment of heavy metal pollution in the urban stream sediments and its tributaries. *Int. J. Environ. Sci. Technol.* **2010**, *7*, 435–446. [CrossRef]
56. Abrahim, G.; Parker, R. Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki estuary, Auckland, New Zealand. *Environ. Monit. Assess.* **2008**, *136*, 227–238. [CrossRef]
57. Tomlinson, D.L.; Wilson, J.G.; Harris, C.R.; Jeffrey, D.W. Problems in the assessment of heavy-metal levels in estuaries and the formation of a pollution index. *Helgol. Meeresunters.* **1980**, *33*, 566–575. [CrossRef]
58. Suresh, G.; Sutharsan, P.; Ramasamy, V.; Venkatachalapathy, R. Assessment of spatial distribution and potential ecological risk of the heavy metals in relation to granulometric contents of Veeranam lake sediments, India. *Ecotoxicol. Environ. Saf.* **2012**, *84*, 117–124. [CrossRef]
59. Stoffers, P.; Glasby, G.P.; Wilson, C.J.; Davis, K.R.; Walter, P. Heavy metal pollution in Wellington Harbour. *N. Z. J. Mar. Freshw. Res.* **1986**, *20*, 495–512. [CrossRef]
60. Förstner, U.; Ahlf, W.; Calmano, W.; Kersten, M. Sediment Criteria Development: Contributions from Environmental Geochemistry to Water Quality Management. In *Sediments and Environmental Geochemistry*; Springer: Berlin/Heidelberg, Germany, 1990; pp. 311–338.
61. Loska, K.; Cebula, J.; Pelczar, J.; Wiechula, D.; Kwapulinski, J. Use of enrichment, and contamination factors together with geoaccumulation indexes to evaluate the content of Cd, Cu, and Ni in the Bybnik water reservoir in Poland. *Water Air Soil Pollut.* **1997**, *93*, 347–365. [CrossRef]
62. Gonzáles-Macías, C.; Schifter, I.; Lluch-Cota, D.B.; Méndez-Rodríguez, L.; Hernández-Vázquez, S. Distribution, enrichment and accumulation of heavy metals in coastal sediments of Salina Cruz Bay, Mexico. *Environ. Monit. Assess.* **2006**, *118*, 211–230. [CrossRef]
63. Chen, C.W.; Kao, C.M.; Chen, C.F.; Dong, C.D. Distribution and accumulation of heavy metals in the sediments of Kaohsiung Harbor, Taiwan. *Chemosphere* **2007**, *66*, 1431–1440. [CrossRef] [PubMed]
64. Saraee, K.R.E.; Abdi, M.R.; Naghavi, K.; Saion, E.; Shafaei, M.A.; Soltani, N. Distribution of heavy metals in surface sediments from the South China Sea ecosystem, Malaysia. *Environ. Monit. Assess.* **2011**, *183*, 545–554. [CrossRef] [PubMed]
65. Maanan, M.; El Barjy, M.; Hassou, N.; Zidane, H.; Zourarah, B.; Maanan, M. Origin and potential ecological risk assessment of trace elements in the watershed topsoil and coastal sediment of the Oualidia lagoon, Morocco. *Hum. Ecol. Risk Assess.* **2017**, *24*, 602–614. [CrossRef]
66. El Barjy, M.; Maanan, M.; Maanan, M.; Salhi, F.; Tnoumi, A.; Zourarah, B. Contamination and environmental risk assessment of heavy metals in marine sediments from Tahaddart estuary (NW of Morocco). *Hum. Ecol. Risk Assess.* **2020**, *26*, 87–102. [CrossRef]
67. Rafiq, F.; Techetach, M.; Boundir, Y.; Achtak, H.; Mandri, B.; Benhamdoun, A.; Cherifi, O.; Dahbi, A. First vertical exploration of organometallic contamination of sediment at the fishing port of Safi (West of Morocco). *Moroc. J. Chem.* **2022**, *10*, 115–126. [CrossRef]

68. Mejjad, N.; Laissaoui, A.; Benmhammed, A.; Fekri, A.; El Hammoumi, O.; Benkdad, A.; Amsil, H.; Chakir, E.M. Potential ecological risk assessment of rare earth elements in sediments cores from the Oualidia lagoon, Morocco. *Soil Sediment Contam. Int. J.* **2022**, *31*, 941–958. [CrossRef]
69. Xu, Z.Q.; Ni, S.J.; Tuo, X.G.; Zhang, C.J. Calculation of heavy metals' toxicity coefficient in the evaluation of potential ecological risk index. *Environ. Sci. Technol.* **2008**, *31*, 112–115.
70. Zhang, L.H.; Du, Y.F.; Wang, D.D.; Gao, S.; Gao, W.H. Distribution patterns and pollution assessments of heavy metals in the Spartina alterniflora salt-marsh wetland of Rudong, Jiangsu province. *Environ. Sci.* **2014**, *35*, 2401–2410. [CrossRef]
71. Soliman, N.F.; Nasr, S.M.; Okbah, M.A. Potential ecological risk of heavy metals in sediments from the Mediterranean coast, Egypt. *J. Environ. Health Sci. Eng.* **2015**, *13*, 70. [CrossRef]
72. Sun, G.; Chen, Y.; Bi, X.; Yang, W.; Chen, X.; Zhang, B.; Cui, Y. Geochemical assessment of agricultural soil: A case study in Songnen-Plain (Northeastern China). *Catena* **2013**, *111*, 56–63. [CrossRef]
73. Mejjad, N.; Laissaoui, A.; Fekri, A.; Hassen, N.E.H.; Benmhammed, A.; El Hammoumi, O.; Benkdad, A.; Amsil, H. Tracking natural and human impact on sediment dynamics using radiometric approach in Oualidia lagoon (Morocco). *Int. J. Environ. Anal. Chem.* **2022**, *102*, 4300–4315. [CrossRef]
74. Kim, Y.; Kim, K.; Kang, H.D.; Kim, W.; Doh, S.H.; Kim, D.S.; Kim, B.K. The accumulation of radiocesium in coarse marine sediment: Effects of mineralogy and organic matter. *Mar. Pollut. Bull.* **2007**, *54*, 1341–1350. [CrossRef]
75. Mejjad, N.; Laissaoui, A.; El-Hammoumi, O.; Benmansour, M.; Benbrahim, S.; Bounouira, H.; Benkdad, A.; Bouthir, F.Z.; Fekri, A.; Bounakhla, M. Sediment geochronology and geochemical behavior of major and rare earth elements in the Oualidia Lagoon in the western Morocco. *J. Radioanal. Nucl. Chem.* **2016**, *309*, 1133–1143. [CrossRef]
76. Zidane, H.; Maanan, M.; Mouradi, A. Environmental and ecological risk of heavy metals in the marine sediment from Dakhla Bay, Morocco. *Environ. Sci. Pollut. Res.* **2017**, *24*, 7970–7981.
77. Wenning, R.J.; Ingersoll, C.G. *Summary of the SETAC Pellston Workshop on Use of Sediment Quality Guidelines and Related Tools for the Assessment of Contaminated Sediments, Fairmont, MT, USA, 17–22 August 2002*; Society of Environmental Toxicology and Chemistry (SETAC): Pensacola, FL, USA, 2002.
78. Zhan, S.; Peng, S.; Liu, C.; Chang, Q.; Xu, J. Spatial and temporal variations of heavy metals in surface sediments in Bohai Bay, North China. *Bull. Environ. Contam. Toxicol.* **2010**, *84*, 482–487. [CrossRef]
79. Gu, Y.G. Heavy metal fractionation and ecological risk implications in the intertidal surface sediments of Zhelin Bay, South China. *Mar. Pollut. Bull.* **2018**, *129*, 905–912. [CrossRef]
80. Zourarah, B.; Maanan, M.; Robin, M. Sedimentary records of anthropogenic contribution to heavy metal content in Oum Er Bia estuary (Morocco). *Environ. Chem. Lett.* **2009**, *7*, 67–78. [CrossRef]
81. Legorburu, I.; Rodríguez, J.G.; Borja, Á.; Menchaca, I.; Solaun, O.; Valencia, V.; Galparsoro, I.; Larreta, J. Source characterization and spatio–temporal evolution of the metal pollution in the sediments of the Basque estuaries (Bay of Biscay). *Mar. Pollut. Bull.* **2013**, *66*, 25–38. [CrossRef] [PubMed]
82. Taylor, S.R.; McLennan, S.M. *The Continental Crust: Its Composition and Evolution*; Blackwell Scientific Publication: Carlton, Australia, 1985; p. 312.
83. Viers, J.; Dupré, B.; Gaillardet, J. Chemical composition of suspended sediments in World Rivers: New insights from a new database. *Sci. Total Environ.* **2009**, *407*, 853–868. [CrossRef] [PubMed]
84. Burton, G.A., Jr. Sediment quality criteria in use around the world. *Limnology* **2002**, *3*, 65–76. [CrossRef]
85. Yi, Y.; Yang, Z.; Zhang, S. Ecological risk assessment of heavy metals in sediment and human health risk assessment of heavy metals in fishes in the middle and lower reaches of the Yangtze river basin. *Environ. Pollut.* **2011**, *159*, 2575–2585. [CrossRef]
86. Liu, J.L.; Wu, H.; Feng, J.X.; Li, Z.J.; Lin, G.H. Heavy metal contamination and ecological risk assessments in the sediments and zoobenthos of selected mangrove ecosystems, South China. *Catena* **2014**, *119*, 136–142. [CrossRef]
87. Ward, J.H. Hierarchical grouping to optimize an objective function. *J. Am. Stat. Assoc.* **1963**, *58*, 236–244. [CrossRef]
88. Hajji, C.; Bendou, A.; Hassou, A. Management of Moroccan solid harbor waste: Comparative analysis and recommendations. *J. Water Environ. Sci.* **2017**, *1*, 59–76.
89. Byrnes, T.A.; Dunn, R.J.K. Boating- and shipping-related environmental impacts and example management measures: A review. *J. Mar. Sci. Eng.* **2020**, *8*, 908. [CrossRef]
90. Warnken, J.; Dunn, R.J.K.; Teasdale, P.R. Investigation of recreational boats as a source of copper at anchorage sites using time-integrated diffusive gradients in thin film and sediment measurements. *Mar. Pollut. Bull.* **2004**, *49*, 833–843. [CrossRef]