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# Heavy Metal Contamination and Ecological Risk Assessment in the Sediment Cores of the Wetlands in Southern Thailand

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**Abstract:** The concentration and distribution of trace metals were determined in sediment cores from the Khuan Khi Sian wetland, Thailand. The sediment cores were collected from seven stations in the dry and wet seasons in 2022. The concentration of Pb, As, and Cd in the dry season were in the range 0.00–60.16, 0.00–6.68, and 0.00–0.92 mg/kg (dry weight), respectively. Meanwhile, the concentration of Pb, As, and Cd in the wet season were in the range 0.00–12.12, 0.00–3.86, and 0.00–0.92 mg/kg (dry weight), respectively. The vertical profiles of metal concentrations in core sediment show a general increase from bottom to top. Average concentrations of heavy metals in the sediments of the Khuan Khi Sian wetland are found to be lower than the sediment quality guideline. In the sediment cores, only As in the dry season exceeded the U.S. EPA standard. The calculated enrichment factor (EF) and the geoaccumulation index (Igeo) indicate that the sediments were moderately polluted with As in some locations. According to the Ri analysis, Pb was low risk but the criteria of ecological risk of As and Cd are considerable and they are considered high risk. This is potentially due to agricultural activities and land use around the wetland areas and municipalities. The concentration of As and Cd should be of concern and subject to regular monitoring.

**Keywords:** heavy metal; sediment cores; environmental risk; wetland; enrichment factor



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## 1. Introduction

Over the past decades, rapid population growth and extensive economic development has led to increased environmental pollution in coastal areas. Various human activities in coastal areas negatively affect the coastal environment because they release pollutants into the marine environment through point sources such as industry, tourism, household activities, and agricultural activities [1–3]. Among the various types of pollution, heavy metals are considered to cause critical environmental problems due to their toxicity, persistence in nature, and bioaccumulation in ecosystems [4,5]. Many studies have shown that heavy metals that accumulate in sediments may not only pollute the environment, but also enter the food chain and have long-term impacts on human health [6,7]. Heavy metals can enter the human body through exposure pathways such as the gastrointestinal tract, inhalation, and skin contact [8]. Several symptoms are associated with heavy metal poisoning in the human system, such as nausea, vomiting, diarrhea, cancer, neurological changes, Alzheimer's disease, and cardiovascular diseases [9–11]. In particular, lead (Pb), arsenic (As) and cadmium (Cd) are listed as priority pollutants by the United States Environmental Protection Agency (U.S. EPA) because they can be toxic and harmful even at low concentrations [12]. Pollution levels of the aquatic environment by heavy metals can be estimated by analyzing water, sediment, and marine organisms [13,14]. Many heavy metals and suspended particles are carried by seawater and accumulate in sediment [15]. Sediments tend to act as a reservoir for heavy metals in the marine environment, and release more heavy metals into seawater when certain environmental conditions change (e.g., salinity, pH, and redox potential). Therefore, sediment acts as both a sink and a source of trace metals [16]. Moreover, sediment cores can reflect the pollution history of aquatic ecosystems [17]. Over the last few decades, sediment cores studies have been shown to be an excellent tool for indicating the effects of anthropogenic activities and natural processes on depositional environments.

Wetlands are major natural protection ecosystems which have been referred to as the kidney of the landscape [18]. Although wetlands provide valuable benefits to human societies such as biodiversity maintenance, fish nursery habitats, water purification, and flood protection [19,20], they receive inputs of heavy metals from land, oceans, and the atmosphere and are considered valuable sinks for heavy metal pollution. In addition, natural wetlands are often used for the management of industrial, agricultural, and domestic wastewater. Increasing heavy metal pollution in wetland ecosystems around the world poses significant ecological risks.

Previous studies have revealed that the Biyyam wetlands in southern India are heavily polluted with heavy metals (Ni, Zn, Mn, Cu, Cd and Pb) due to natural and human activities. In particular, Ni, Cd, and Pb were found to have exceeded the global average shale value [21]. Heavy metal pollution in the Raoyanghe Wetland, China, also poses significant ecological risks [22]. Additionally, Chunming Li 2022 reported that trends in the occurrence frequency of Cd, Zn, Cu, Pb, and Hg in wetlands have increased over the last three decades [23].

The Khuan Khi Sian is one of the most important natural wetlands in Thailand. In addition to being an important natural ecological resource, a part of the lake is also designated as the first Ramzar site in Thailand [24]. This area has a high diversity of wetland habitats in addition to being the site of many human activities such as tourism, local communities, rubber plantations, and mixed orchards [25]. Existing studies on heavy metals in Thailand have primarily focused on farmlands, coastal areas, rivers, and industrial areas, but not on wetland areas [26–28]. Therefore, the study of heavy metals and ecological risk in wetlands is insufficient.

The goal of this study was to assess the contamination and distribution of heavy metals (Arsenic: As, Cadmium: Cd, and Lead: Pb) in wetland forest sediment cores. It is known that Pb, Cd, and As are harmful pollutants. The potential ecological risks of heavy metals in sediment cores were studied with the enrichment factor (EF), the Geoaccumulation index (Igeo), and the ecological risk index (Ri), while the pollution levels in the studied area were also compared with those in areas worldwide. The study results will be used as baseline data for the present state of metals in sediment in wetland areas. In addition, this information is very important to enable better management of heavy metal pollution in wetlands.

## 2. Materials and Methods

### *2.1. Study Area*

The Thale Noi Non-Hunting Area is one of the largest natural freshwater lakes in Southeast Asia [29], located in the Phatthalung province, Thailand. The Khuan Khi Sian wetland is located in the North of Thale Noi at an altitude of 7°49′ to 7°51′ N and longitude of 100°07′ to 100°09′ E with a total area of 59.58 square kilometers (Figure 1). This area has a high diversity of wetland habitat, including grassland, freshwater lake, Melaleuca swamp forest, rice fields, rubber plantations, mixed orchards, as well as being home to local communities, and hosting tourism and other human uses [30]. A wetland is an area that is completely submerged in water all year. The vegetation in the study area consists primarily of *Melaleuca leucadendron*, which serves as a nesting site for large water birds, as well as aquatic plants such as water lettuce.

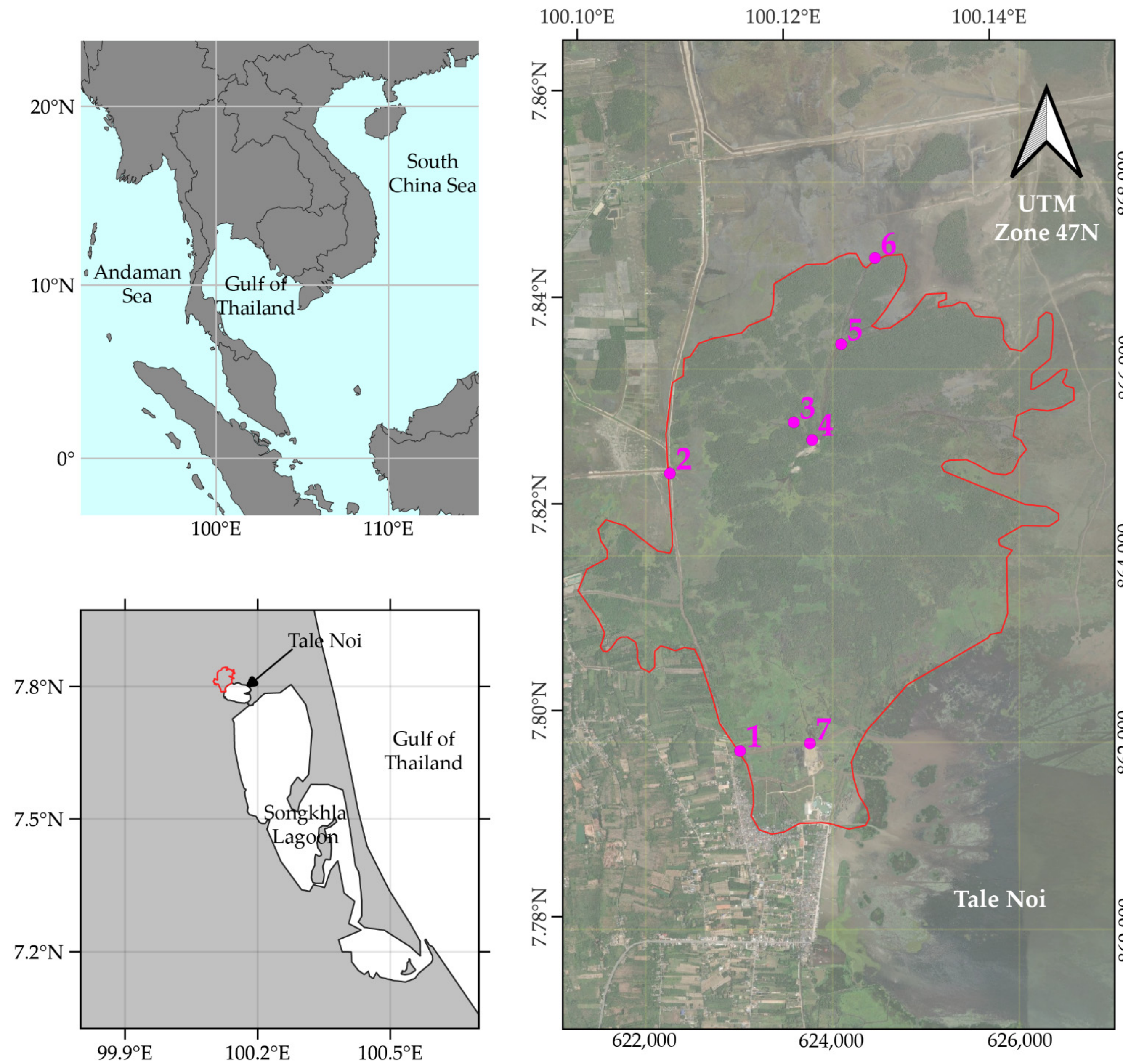


**Figure 1.** Map of the study area and the location of the sampling site. (Noted: the numbers represented samping stations 1–7).

## 2.2. Sample Collection and Storage

Sediments were collected from seven stations in the wetland area (Figure 1) using acrylic sediment cores with a 5 cm diameter and 50 cm in depth. The samples were collected from the study area on two dates, in March, 2022 (dry season) and June, 2022 (rainy season). Each core was sliced into 4 cm thick sections, placed in plastic resealable bags, and kept at −20 °C until analysis. The wet sediments were oven dried at 60 °C, ground with a mortar and pestle, and sieved through a 1 mm nylon sieve to obtain a fine homogeneous powder before analysis.

## 2.3. Digestion Procedure

All samples were prepared according to an adapted U.S. EPA method to determine the total heavy metals for Pb, As, and Cd in the core sediments [31]. Typically, 0.5 g of a sample was put in a Teflon digestion vessel and digested with 10 mL of 65% $HNO_3$ (Merck, Suprapur, Darmstadt, Germany). The samples were heated in a microwave oven at 175 °C for 10 min. After the samples were cooled, the obtained solution was filtered using Whatman paper No. 40. To this, 100 mL of Milli-Q water was added and the samples were stored in acid-cleaned polyethylene storage bottles for ICP-OES analysis.

### 2.4. Analysis of Metals

All chemicals were of analytical grade and were used without further purification. All glassware used for analysis was immersed in nitric acid overnight (3% $HNO_3$, Merck) and then rinsed with Milli-Q deionized water several times. Heavy metal concentrations were analyzed with an Inductively Coupled Plasma Optical Emission Spectroscopy 5900 (ICP-OES, Agilent 7300DV, Santa Clara, CA, USA). MESS-4 was used as the marine sediment certified reference material. The analytical value was within 90% of the certified value. The efficiency of the analysis was assessed by three replicates. The concentrations of heavy metals in blank samples were always below the detection limits. The detection limit was 0.1 mg/kg for Fe, Pb, As, and Cd.

### 2.5. Data Processing and Statistical Analysis

All calculations and statistics were conducted using MS Excel 2007 (Office Professional Plus 2019).

#### 2.5.1. The Enrichment Factor (EF)

The enrichment factor (EF) was used to assess the degree of pollution in the sediment to identify various sources of pollution, including natural processes or anthropogenic activities [32]. EF was calculated by Equation (1):

$$EF = (C_X/C_{Fe})_{sediment}/(C_X/C_{Fe})_{reference} \quad (1)$$

where $(C_X/C_{Fe})_{sediment}$ is the ratio of metal and Fe concentrations in the sediment sample and $(C_X/C_{Fe})_{reference}$ is the ratio of metal and Fe concentrations in the background [33].

In the present study, the regional background values were adopted from Taylor and Mclennan [34] and Shazili et al. (1999) who reported on offshore sediments in the Gulf of Thailand [35]. The background concentrations for Fe, Pb, As, and Cd were 12,200 µg/g, 29.9 µg/g, 1.8 µg/g, and 0.35 µg/g, respectively. Fe was selected as a normalizer for heavy metals in the sediment because it is a naturally abundant element and a conservative element in the Earth [36]. According to Dimitri Ekissi (2021), if $EF < 1$, this indicates no enrichment of the metal; if $1 \leq EF \leq 3$, there is minor enrichment; if $3 \leq EF \leq 5$, there is moderate enrichment; if $5 \leq EF \leq 10$, there is moderately to severe enrichment; if $10 \leq EF \leq 25$, there is severe enrichment; If $25 \leq EF \leq 50$, there is very severe enrichment; and if $EF > 50$, there is extreme enrichment [37].

#### 2.5.2. The Geoaccumulation Index (Igeo)

The geoaccumulation index (Igeo) was used to determine the level of metal contamination in sediment which was calculated using Equation (2) [38]:

$$Igeo = \log 2Cn/1.5 \times Bn \quad (2)$$

where Cn is the measured concentration of the sediment for heavy metals, and Bn is the geochemical background concentration of the heavy metals. A factor of 1.5 was used to minimize the effect of possible variations in the background values due to lithogenic effects in the sediments [39]. The geoaccumulation index is classified into seven classes of quality for sediments: $Igeo > 5$ means extremely contaminated; $4 < Igeo \leq 5$—strongly to extremely contaminated; $3 < Igeo \leq 4$—strongly contaminated; $2 < Igeo \leq 3$—moderately to strongly contaminated; $1 < Igeo \leq 2$—moderately contaminated; $0 < Igeo < 1$—uncontaminated to moderately contaminated; and $Igeo < 0$—uncontaminated [40].

#### 2.5.3. The Ecological Risk Index ($R_j$)

The ecological risk index ($R_j$) was calculated to assess the degree of heavy metal pollution in sediment cores of the Khuan Khi Sian wetland based on the toxicity of heavy metals and the response of the environment. The *Ri* was calculated according to Equation (3) [41]:

$$Ri = \sum_{i=1}^{n} Ei \tag{3}$$

$$Ei = Ti \cdot \left(\frac{Ci}{Co}\right) \tag{4}$$

where *Ri* is the sum of the possible ecological risk factors for heavy elements in sediments, *Ei* is the potential ecological risk factor, and *Ti* is the toxic response factor of certain metals. *Ti* values for Pb, As, and Cd are 5, 10, and 30, respectively, according to the Hakenson report [42]. *Ci* is the metal concentration of the sediments and $C_0$ is the background metal concentration. The criteria for *Ei* and *Ri* values are shown in Table 1.

**Table 1.** Classification of potential ecological risk for heavy metals in sediments.

| Range of Ei Value | Level of Comprehensive Potential Ecological Risk |
|---|---|
| $Ei < 150$ | Low |
| $150 \leq Ei \leq 300$ | Moderate |
| $300 \leq Ei \leq 600$ | Considerable |
| $600 \leq Ei$ | High |

## 3. Results and Discussion

Table 2 shows the mean, minimum and maximum concentrations of Pb, As, and Cd (mg/kg) as measured in sediment cores from seven sampling sites in two seasons. The results show that the average total concentration in dry and wet seasons are as follows: Pb (16.35 mg/kg and 7.41 mg/kg), As (3.54 mg/kg and 2.02 mg/kg) and Cd (0.28 mg/kg and 0.48 mg/kg), respectively. The concentrations of Pb in the sediment samples ranged between 0.00–60.16 mg/kg and 0.00–12.12 mg/kg at all sites and depths, in dry and wet seasons, respectively. Meanwhile, the concentrations of As in the sediment cores ranged between 0.00–6.68 mg/kg and 0.00–3.86 mg/kg in the dry and wet seasons, respectively. The concentrations of Cd in the sediment cores ranged from 0.00–1.74 mg/kg for all seasons and depths. It is worth noting that the average concentrations of these three heavy metals fell in the following orde in both seasons: Pb > As > Cd. It is possible that high levels of Pb are caused by petroleum oil released from boats during tourism activities and fishing in the Thale Noi Non-Hunting area. Wetlands are well known to be home to over 280 species of aquatic birds [29]. As a result, many tourists visit Thale Noi Non-Hunting Area to see a waterbird. However, high Cd concentrations were also observed during the wet season when there is less tourism, and less associated petroleum oil released. This could be due to high Cd precipitation, which causes higher Cd run-off. Furthermore, these findings are consistent with another study on the seasonal bioavailability of Cd in sediments published by Sowunmi et al. It was discovered that Cd was mostly found in the residual fraction during the wet season as opposed to the dry season [43] indicating its potential mobility. In the dry season, the available fraction (Carbonate, Fe/Mn Oxide, and organic) has a high affinity for Cd.

**Table 2.** Heavy metal concentrations (mg/kg dry weight) in the sediment cores of the Khuan Khi Sian wetland.

| Stations | Depth (cm) | Pb (Dry) | Pb (Wet) | As (Dry) | As (Wet) | Cd (Dry) | Cd (Wet) |
|---|---|---|---|---|---|---|---|
| 1 | 0–4 | 15.71 | 5.63 | 2.93 | 1.70 | 0.46 | 0.19 |
| | 4–8 | 13.93 | 5.31 | 3.72 | 2.04 | 0.41 | 0.42 |
| | 8–12 | 18.03 | 3.20 | 3.57 | 1.90 | 0.40 | 0.06 |
| | 12–16 | 24.32 | 7.95 | 4.89 | 1.11 | 0.49 | 0.07 |
| | 16–20 | 21.92 | 5.78 | 5.39 | 1.17 | 0.42 | 0.10 |
| | 20–24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | 0–4 | 18.14 | 4.85 | 4.38 | 1.50 | 0.92 | 0.20 |
| | 4–8 | 13.94 | 7.02 | 4.95 | 3.16 | 0.61 | 0.41 |
| | 8–12 | 13.32 | 8.84 | 4.33 | 3.62 | 0.24 | 0.46 |
| | 12–16 | 15.90 | 8.26 | 6.06 | 2.23 | 0.30 | 0.36 |
| | 16–20 | 15.56 | 7.79 | 5.57 | 1.96 | 0.46 | 0.29 |
| | 20–24 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | 0–4 | 46.79 | 6.68 | 4.98 | 1.85 | 0.40 | 0.29 |
| | 4–8 | 13.51 | 7.23 | 3.23 | 2.19 | 0.22 | 0.33 |
| | 8–12 | 17.71 | 8.86 | 4.90 | 1.70 | 0.37 | 0.63 |
| | 12–16 | 17.29 | 8.61 | 4.00 | 1.43 | 0.33 | 0.61 |
| | 16–20 | 17.10 | 8.40 | 4.54 | 2.06 | 0.37 | 0.58 |
| | 20–24 | 15.06 | 8.73 | 3.72 | 1.69 | 0.36 | 0.59 |
| 4 | 0–4 | 6.60 | 6.23 | 1.11 | 1.56 | 0.12 | 0.31 |
| | 4–8 | 6.98 | 5.71 | 2.58 | 1.48 | 0.26 | 0.14 |
| | 8–12 | 9.53 | 6.96 | 2.02 | 1.95 | 0.28 | 0.19 |
| | 12–16 | 8.06 | 5.82 | 2.28 | 0.99 | 0.26 | 0.12 |
| | 16–20 | 4.51 | 6.24 | 1.92 | 1.44 | 0.18 | 0.18 |
| | 20–24 | 5.93 | 5.83 | 2.08 | 1.25 | 0.17 | 0.24 |
| 5 | 0–4 | 60.16 | 6.39 | 4.62 | 1.54 | 0.38 | 0.41 |
| | 4–8 | 13.35 | 6.82 | 3.64 | 1.47 | 0.30 | 0.46 |
| | 8–12 | 12.75 | 6.22 | 2.70 | 2.57 | 0.27 | 0.35 |
| | 12–16 | 10.99 | 6.81 | 4.07 | 2.21 | 0.15 | 0.43 |
| | 16–20 | 13.01 | 7.49 | 3.93 | 2.06 | 0.15 | 0.35 |
| | 20–24 | 13.36 | 11.28 | 4.08 | 3.86 | 0.18 | 0.60 |
| 6 | 0–4 | 33.60 | 9.72 | 4.36 | 2.82 | 0.12 | 0.61 |
| | 4–8 | 13.60 | 10.45 | 2.35 | 3.44 | 0.07 | 0.64 |
| | 8–12 | 14.36 | 8.45 | 2.40 | 1.39 | 0.06 | 0.54 |
| | 12–16 | 14.01 | 12.12 | 3.41 | 3.23 | 0.08 | 0.94 |
| | 16–20 | 13.42 | 11.04 | 2.40 | 2.31 | 0.02 | 0.85 |
| | 20–24 | 14.92 | 10.30 | 2.54 | 3.29 | 0.06 | 0.82 |
| 7 | 0–4 | 42.10 | 9.69 | 2.96 | 2.57 | 0.11 | 0.59 |
| | 4–8 | 15.56 | 11.15 | 3.99 | 3.39 | 0.09 | 0.76 |
| | 8–12 | 15.02 | 10.02 | 3.12 | 2.61 | 0.10 | 0.92 |
| | 12–16 | 13.55 | 9.47 | 3.54 | 2.26 | 0.05 | 1.13 |
| | 16–20 | 14.07 | 3.38 | 4.75 | 2.09 | 0.05 | 1.06 |
| | 20–24 | 19.09 | 10.56 | 6.68 | 1.76 | 0.14 | 1.74 |
| **Average** | | 16.35 | 7.41 | 3.54 | 2.02 | 0.25 | 0.48 |
| **Min** | | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Max** | | 60.16 | 12.12 | 6.68 | 3.86 | 0.92 | 1.74 |

## 4. Discussion

Table 2 shows the distribution of heavy metals at different depths in sediment cores, and Figure 2 shows the average concentrations for both seasons. Each heavy metal in the core sediments had its own distribution characteristics. The dry season found a high concentration of Pb in the upper segments of the sediment cores, while the wet season found a steady concentration in the entire section. However, in both seasons, a high concentration of As was found in the middle segment. Furthermore, a high concentration of Cd was discovered in the 0–4 cm segment. In summary, the high concentration of heavy metals found in the upper and medium segments of the sediment cores suggests that metals delivery to sediments has increased in recent years. These high concentrations are most likely due to an increase in anthropogenic pollutant inputs from municipalities, agricultural activities, and tourism. Similarly, core sediments from coastal areas in the eastern part of Malaysia showed enrichment of As, Cd, Ni, Pb and Zn in the upper layers, suggesting there had been an excess of anthropogenic loading in the recent year more than the earlier years [44]. In both seasons, station 4 has lower heavy metal readings than the other stations, which is important to note. Most likely this is because the station is in a sand-covered region, on a little hill in the center of a marsh. By contrast, most stations are covered in mud (based on sight), and mud sediment often absorbs heavy metals more effectively than sandy sediment.

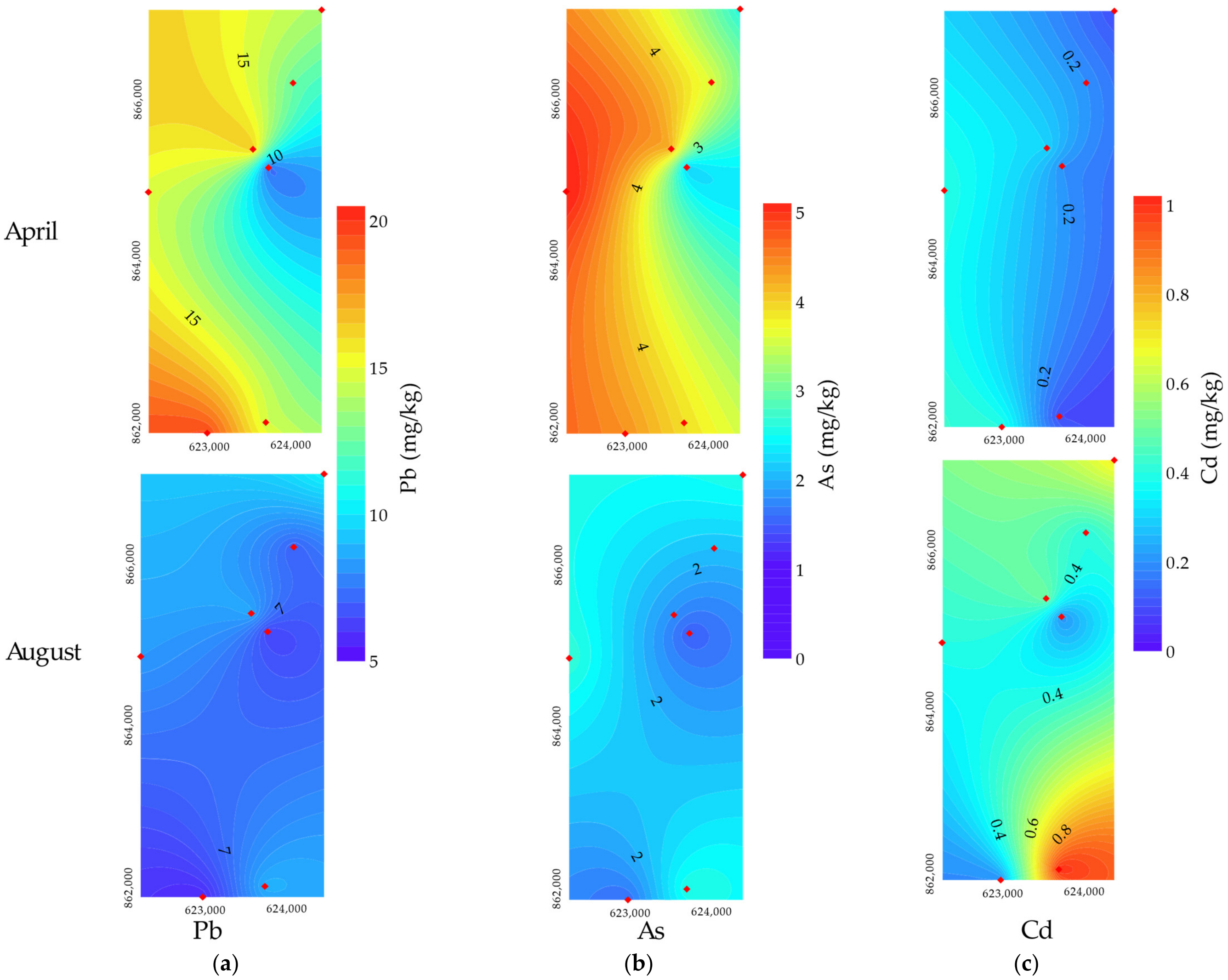


**Figure 2.** Heavy metal distribution (mg/kg dry weight) in the sediment cores of the Khuan Khi Sian wetland: (**a**) Pb, (**b**) As, and (**c**) Cd. (Note: April = dry season; August = wet season.).

The concentrations of metals in the sediment cores showed significant seasonal and spatial variations (Figure 2). This suggests that seasonal changes affect the distribution of metals in the sediment core. In the dry season, Pb and As had higher concentrations than in the wet season. This could be due to the effect of runoff and rainfall which can remove heavy metals from farmland and which could facilitate the leaching of the soil and dilute the metal concentration in the wet season [45]. Moreover, the levels of Pb reported in this present study were in the same range as Pb levels found in sediments from Songkhla lake (Thailand) by many other researchers [45]. However, high concentrations of Cd was observed in the wet season. This might be due to high precipitation of Cd which leads to higher run-off of Cd. In addition, these results correspond with another study on seasonal bioavailability of Cd in sediments which was reported by Sowunmi et al. [43]. They showed that Cd was mostly in the residual fraction in the wet season as compared to the dry season, increasing its potential mobility. By contrast, the available fraction (Carbonate, Fe/Mn Oxide and organic) has a high affinity for Cd in the dry season.

The heavy metal concentrations in the sediment cores of the study area were assessed by comparing them with three sets of sediment quality guidelines (SQGs) shown in Table 3. Our assessment of sediment contamination was based on U.S. EPA [46], the threshold effect concentrations (TEC)/probable effect concentrations (PEC) [47], and the effect range low (ERL)/effect range median (ERM) [48]. A comparison of the SQGs indicates that the average concentrations of Pb and Cd in this study were lower than their background values and they did not pose any environmental risks in any of the investigated sites. According to the U.S. EPA, concentrations of As during the dry season indicated moderate pollution. Agricultural activities and crops may also contribute to increased metal concentrations during the dry season. Furthermore, Pradit et al. 2013 [45] reported a high As concentration (20–22 mg/kg dry weight) in the Thale Noi area of Songkhla lake, Thailand, which had previously been reported to be considerably lower in 2007 (5.7–10.8 mg/kg dry weight) [49]. In our study, As concentration was found to be much lower than the local background value. However, As concentrations should be monitored on a regular basis.

**Table 3.** Sediment quality guidelines (SQGs) for heavy metals.

| Element | U.S. EPA Toxicity Classifications | | | MacDonald et al., 2000 | | NOAA | |
|---|---|---|---|---|---|---|---|
| | Nonpolluted | Moderately Polluted | Heavily Polluted | TEC | PEC | ERL | ERM |
| Pb | <40 | 40–60 | >60 | 36 | 130 | 46.7 | 218 |
| As | <3 | 3–8 | >8 | 9.8 | 33 | 8.2 | 70 |
| Cd | * | * | >6 | 0.99 | 5.0 | 1.2 | 9.6 |

* Lower limits not established.

### 4.1. Environmental Risk Assessment of Heavy Metals in Sediment Cores

The EF and Igeo values of Pb, As and Cd from the seven sampling stations are presented in Table 4. The EF values of heavy metals in the dry season varied as follows: 0.24–2.07 (mean = 0.63 $\pm$ 0.43), 1.08–6.10 (mean = 2.31 $\pm$ 0.96), and 0.05–3.03 (mean = 0.89 $\pm$ 0.74) for Pb, As, and Cd, respectively. The EF values of heavy metals in the wet season varied as follows: 0.08–0.90 (mean = 0.38 $\pm$ 0.13), 0.50–3.93 (mean = 1.73 $\pm$ 0.63), and 0.63–2.50 (mean = 1.71 $\pm$ 0.44) for Pb, As and Cd, respectively. The average EF values of Pb (dry and wet season) and Cd (dry season) were less than 1. These values indicate no enrichment at the sampling stations. However, the As average concentration was in the range 1–3 which indicates minor enrichment. Generally, metal elements with EF between 0.5 and 1.5 are considered to originate from the crustal materials or natural processes, whereas those metal elements with EF higher than 1.5 is caused by anthropogenic activities [50]. Generally, As can occur naturally in sediments because of the weathering of the parent material [51]. However, human activities, such as agricultural activities, mixed orchards, fertilizers used in agricultural activities, and rubber plantations, may contribute to the heavy metal deposition around the wetland areas, causing the high As content in sediment cores [25,30]. Generally, As compounds such as sodium arsenide [52], monosodium methane arsonate [53], and dimethylarsinic acid [54] are used in agricultural activities as weed killers. Moreover, the high As contents in chemical fertilizers may be transported by agricultural wastewater from land to the wetland directly. In addition, agricultural industries such as rubber plantations are also located around the sampling siteswhich may result in contamination of the sediments and waters in these areas. The Igeo values of heavy metals in the dry season varied as follows: 0.05–0.41 (mean = 0.13 ± 0.08), 0.22–1.23 (mean = 0.47 ± 0.19), and 0.01–0.62 (mean = 0.18± 0.15) for Pb, As and Cd, respectively. The Igeo values of heavy metals in the wet season varied as follows: 0.02–0.18 (mean = 0.08 ± 0.03), 0.10–0.79 (mean = 0.35 ± 0.13), and 0.13–0.51 (mean = 0.35± 0.09) for Pb, As and Cd, respectively. These results indicate that the average of Igeo values were less than 1, meaning there was little to moderate caused by the heavy metals in this area.

**Table 4.** The Enrichment factor (EF) and geoaccumulation index (Igeo) of sediment cores.

| Values | Enrichment Factor (EF) | | | | | | Geoaccumulation Index (Igeo) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pb | | As | | Cd | | Pb | | As | | Cd | |
| | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet | Dry | Wet |
| Mean | 0.63 | 0.38 | 2.31 | 1.73 | 0.89 | 1.71 | 0.13 | 0.08 | 0.47 | 0.35 | 0.18 | 0.35 |
| S.D. | 0.43 | 0.13 | 0.96 | 0.63 | 0.74 | 0.44 | 0.08 | 0.03 | 0.19 | 0.13 | 0.15 | 0.09 |
| Min | 0.24 | 0.08 | 1.08 | 0.50 | 0.05 | 0.63 | 0.05 | 0.02 | 0.22 | 0.10 | 0.01 | 0.13 |
| Max | 2.07 | 0.90 | 6.10 | 3.93 | 3.03 | 2.50 | 0.41 | 0.18 | 1.23 | 0.79 | 0.62 | 0.51 |

### *4.2. The Ecological Risk Index (Ri)*

Ri was calculated according to the method proposed by Hakanson and is shown in Figure 3. The Ri value of Pb in the dry season and wet season are 114 and 52, respectively, which indicates low ecological risk from Pb pollution. The level of metal ecological risk of As in dry and wet seasons is 826 and 471, respectively, which also suggests low to medium ecological risk. Among the tested metals, Cd in the sediment showed the highest ecological risk in both dry and wet seasons which was considered most likely to be affected by external factors.

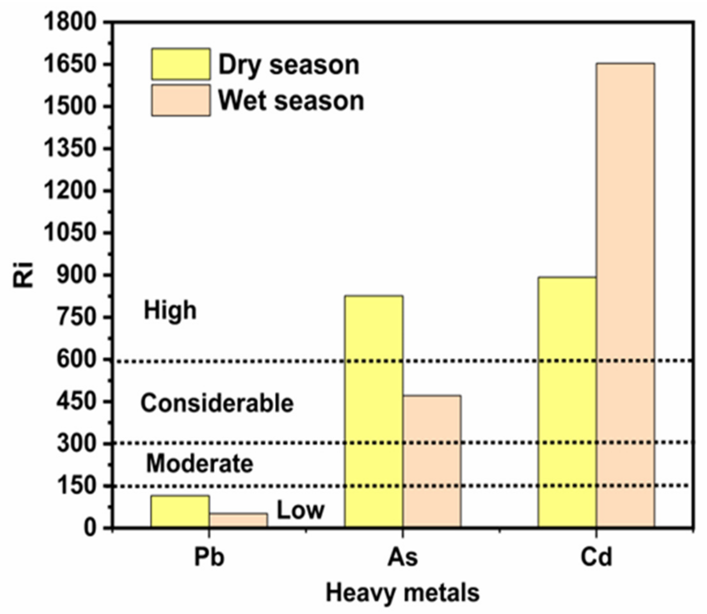


**Figure 3.** The values of the potential ecological risk index.

The accumulation of heavy metals in the sediment cores was compared with that in various areas around the world (Table 5). The concentration of Pb of this study is higher than that of the Orogodo river in southern Nigeria but still lower than of many areas such as Dachan Bay (China), Quanzhou (China), the Baltic Sea, South china sea (Hongkong) and Soline Bay (Croatia). In addition, the concentration of Pb has clearly increased around the wetland and bay areas in southern Thailand since Pradit's work a few years ago. For Cd, the sediment concentration is lower than that of most other areas except Dachan bay (China), Pattani bay, and Setiu wetland in Thailand, Bothnian Bay, Baltic Sea, and Xingyun lake, China. Although the As average concentration in this study indicates minor enrichment, the concentration of As is still lower than in all other countries. However, it remains a concern that all the heavy metals exceeded the sediment quality standard and they should be regularly monitored.

**Table 5.** Heavy metal concentrations (mg/kg) in sediment cores of the Khuan Khi Sian wetland compared to different parts of the world.

| Locations | Values | Pb (mg/kg) | As (mg/kg) | Cd (mg/kg) | Refs. |
|---|---|---|---|---|---|
| Khuan Khi Sian wetland, Thailand | Mean (Dry) | 16.37 | 3.54 | 0.28 | This study |
| | Mean (Wet) | 7.41 | 2.02 | 0.48 | |
| | Min-Max (Dry) | 0.00–60.2 | 0.00–6.70 | 0.13–0.40 | |
| | Min-Max (Wet) | 0.00–12.1 | 1.69–2.45 | 0.37–0.57 | |
| Soline Bay, Croatia | Min-Max | 28.5–67.3 | - | 0.06–0.12 | [55] |
| Pattani Bay Thailand | Min-Max (Dry) | 6.90–11.70 | 2.03–5.93 | 0.00–0.01 | [26] |
| | Min-Max (Wet) | 2.40–11.48 | 6.90–11.70 | 0.01–0.02 | |
| Setiu wetland, Thailand | Min-Max (Dry) | 1.07–2.34 | 0.47–1.02 | 0.00–0.00 | |
| | Min-Max (Wet) | 0.63–1.56 | 1.07–2.34 | 0.00–0.00 | |
| Kochi Estuary, India | Min-Max | 33.4–98.9 | - | 6.05–29.4 | [56] |
| Orogodo river, Southern Nigeria | Min-Max (Dry) | 0.8–25.7 | - | - | [57] |
| | Min-Max (Wet) | 0.6–6.5 | | | |
| Xingyun lake, China | Min-Max | 10.50–95.07 | - | 0.13–1.13 | [58] |
| | Mean | 25.8 | 10.7 | 0.168 | |
| Quanzhou, China | Min-Max | 34.3-100. | - | 0.28-0.89 | [59] |
| | Mean | 57.5 | 17.4 | 0.56 | |
| Dachan Bay, China | Min-Max | 42.7–130 | 8.94–25.2 | 0.19–1.79 | [60] |
| | Mean | 58.4 | 15.9 | 0.65 | |
| | Min-Max | 33.0–70.5 | 12.9–20.1 | 0.35–1.19 | |
| Northern China | Min-Max | 10.0–43.6 | 3.2–17.0 | 0.040–0.360 | [61] |
| Bothnian Bay, Baltic Sea | Mean | 40.2 | - | 0.4 | [62] |
| The west Baltic | Mean | 56.6 | - | 5.5 | |
| South China sea, Hongkong | Min-Max | 20.0–108.0 | - | 1.5–2.5 | [63] |

## 5. Conclusions

In summary, this research work focused on evaluating the concentration and distribution of heavy metals (Pb, As and Cd) in sediment cores collected from the Khuan Khi Sian wetland, Thailand. It is interesting that the mean concentrations of these three heavy metals followed the same pattern in both seasons, namely: Pb > As > Cd. From an environmental risk assessment of heavy metal in sediment cores, the study revealed no enrichment pollution levels of Pb and Cd, while As had a higher enrichment factor than the other metals, and the Igeo value for As was classified as uncontaminated to moderately contaminated. The potential ecological risk index of As and Cd collected from the study areas ranged from significant to high risk. As a result, As and Cd concentrations in this area should be continuously monitored in order to reduce the associated risks. Future study should focus on the potential source of heavy metal deposits in the wetland area, as well as the seasonal current circulation model, to gain a better understanding of the metal distribution in the sediment core.

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## References


1. Chen, Y.-F.; Shi, Q.-Y.; Qu, J.-Y.; He, M.-X.; Li, Q. A pollution risk assessment and source analysis of heavy metals in sediments: A case study of Lake Gehu, China. *Chin. J. Anal. Chem.* **2022**, *50*, 100077. [CrossRef]
2. Chettri, U.; Chakrabarty, T.K.; Joshi, S.R. Pollution index assessment of surface water and sediment quality with reference to heavy metals in Teesta River in Eastern Himalayan range, India. *Environ. Nanotechnol. Monit. Manag.* **2022**, *18*, 100742. [CrossRef]
3. Yang, J.; Xu, H.; Wang, X. Impact of tourism activities on the distribution and pollution of soil heavy metals in natural scenic spots on the northern slope of Tianshan Mountain. *PLoS ONE* **2022**, *17*, e0267829. [CrossRef] [PubMed]
4. Zheng, B.; Lu, S.; Wu, J.; Guo, X.; Wu, F.; Li, X.; He, Q.; Fu, Z.; Xu, L. Heavy metal distribution in Tiaoxi River's sediment. *Environ. Sci. Pollut. Res.* **2018**, *25*, 2603–2613. [CrossRef] [PubMed]
5. Ali, H.; Khan, E.; Ilahi, I. Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *J. Chem.* **2019**, *2019*, 6730305. [CrossRef]
6. Fernandez-Maestre, R.; Johnson-Restrepo, B.; Olivero-Verbel, J. Heavy metals in sediments and fish in the Caribbean coast of Colombia: Assessing the environmental risk. *Int. J. Environ. Res.* **2018**, *12*, 289–301. [CrossRef]
7. Briffa, J.; Sinagra, E.; Blundell, R. Heavy metal pollution in the environment and their toxicological effects on humans. *Heliyon* **2020**, *6*, e04691. [CrossRef]
8. Witkowska, D.; Slowik, J.; Chilicka, K. Heavy metals and human health: Possible exposure pathways and the competition for protein binding sites. *Molecules* **2021**, *26*, 6060. [CrossRef]
9. Mitra, S.; Chakraborty, A.J.; Tareq, A.M.; Emran, T.B.; Nainu, F.; Khusro, A.; Idris, A.M.; Khandaker, M.U.; Osman, H.; Alhumaydhi, F.A.; et al. Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity. *J. King Saud Univ. Sci.* **2022**, *34*, 101865. [CrossRef]
10. Bakulskia, K.M.; Seob, Y.A.; Hickmana, R.C.; Brandta, D.; Vadaria, H.S.; Hu, H.; KyunPark, S. Heavy Metals Exposure and Alzheimer's Disease and Related Dementias. *J. Alzheimer's Dis.* **2020**, *76*, 1215–1242. [CrossRef]
11. Balali-Mood, M.; Naseri, K.; Tahergorabi, Z.; Khazdair, M.R.; Sadeghi, M. Toxic Mechanisms of Five Heavy Metals: Mercury, Lead, Chromium, Cadmium, and Arsenic. *Front. Pharmacol.* **2021**, *12*, 643972. [CrossRef] [PubMed]
12. US EPA. *Framework for Metals Risk Assessment*; EPA-120/R-07/001; U.S. Environmental Protection Agency, Office of the Science Advisor: Washington, DC, USA, 2007; pp. 1–172.
13. Kobkeatthawin, T.; Sirivithayapakorn, S.; Nitiratsuwan, T.; Muenhor, D.; Loh, P.-S.; Pradit, S. Accumulation of trace metal in sediment and soft tissue of Strombus canarium in a tropical remote island of Thailand. *J. Mar. Sci. Eng.* **2021**, *9*, 991. [CrossRef]
14. Huang, Z.; Liu, C.; Zhao, X.; Dong, J.; Zheng, B. Risk assessment of heavy metals in the surface sediment at the drinking water source of the Xiangjiang River in South China. *Environ. Sci. Eur.* **2020**, *32*, 23. [CrossRef]
15. Tan, B.; Liu, C.; Tan, X.; You, X.; Dai, C.; Liu, S.; Li, J.; Li, N. Heavy metal transport driven by seawater-freshwater interface dynamics: The role of colloid mobilization and aquifer pore structure change. *Water Res.* **2022**, *217*, 118370. [CrossRef]
16. Beier, T.; Opp, C.; Hahn, J.; Zitzer, N. Sink and source functions for metal(loid)s in sediments and soils of two water reservoirs of the Ore Mountains, Saxony, Germany. *Appl. Sci.* **2022**, *12*, 6354. [CrossRef]
17. Shi, C.; He, H.; Xia, Z.; Gan, H.; Xue, Q.; Cui, Z.; Chen, J. Heavy metals and Pb isotopes in a marine sediment core record environmental changes and anthropogenic activities in the Pearl River Delta over a century. *Sci. Total Environ.* **2022**, *814*, 151934. [CrossRef] [PubMed]
18. Lin, Y.; Luo, K.; Su, Z.; Wu, Y.; Xiao, W.; Qin, M.; Lin, J.; Zhang, S.; Zhang, Y.; Jiang, Y.; et al. Imposed by urbanization on soil heavy metal content of lake wetland and evaluation of ecological risks in East Dongting Lake. *Urban Clim.* **2022**, *42*, 101117. [CrossRef]
19. Dang, K.B.; Phan, T.T.H.; Nguyen, T.T.; Pham, T.P.N.; Nguyen, M.H.; Dang, V.B.; Hoang, T.T.H.; Ngo, V.L. Economic valuation of wetland ecosystem services in northeastern part of Vietnam. *Knowl. Manag. Aquat. Ecosyst.* **2022**, *423*, 12. [CrossRef]
20. Barbier, E.B. Valuing ecosystem services for coastal wetland protection and restoration: Progress and challenges. *Resources* **2013**, *2*, 213–230. [CrossRef]
21. Nimmi, N.; Shiji, M.; Harikumar, P.S. Assessment of heavy metal contamination and ecological risk of core sediments in a coastal wetland of India. *Soil Sediment Contam.* **2022**, *31*, 886–904.
22. Wang, X.; Sun, Y.; Li, S.; Wang, H. Spatial distribution and ecological risk assessment of heavy metals in soil from the Raoyanghe Wetland, China. *PLoS ONE* **2019**, *14*, e0220409. [CrossRef]
23. Li, C.; Wang, H.; Liao, X.; Xiao, R.; Liu, K.; Bai, J.; Li, B.; He, Q. Heavy metal pollution in coastal wetlands: A systematic review of studies globally over the past three decades. *J. Hazard. Mater.* **2022**, *424*, 127312. [CrossRef] [PubMed]
24. Kaewdee, W.; Thirakhupt, K.; Tunhikorn, S. Population of waterbirds in the breeding colony at Khuan Khi Sian, Thailand's First Ramsar Site. *Nat. Hist. J. Chulalongkorn Univ.* **2002**, *2*, 51–58.
25. Kanchanasaka, B.; Tong-aree, S.; La-ong, S. Reproductive biology and food habits of some birds in Thale Noi Non-hunting Area. *Wildl. J. Thail.* **1986**, *6*, 1–36. (In Thai)

26. Pradit, S.; Shazili, N.A.M.; Towatana, P.; Saengmanee, W. Trace metals, grain size and organic matter in sediment from a coastal area of Thailand and Malaysia. *Aquat. Ecosyst. Health Manag.* **2016**, *19*, 345–354. [CrossRef]
27. Mingkhwan, R.; Worakhunpiset, S. Heavy Metal Contamination Near Industrial Estate Areas in Phra Nakhon Si Ayutthaya Province, Thailand and Human Health Risk Assessment. *Int. J. Environ. Res. Public Health* **2018**, *15*, 1890. [CrossRef] [PubMed]
28. Ta, A.T.; Babel, S. Microplastics pollution with heavy metals in the aquaculture zone of the Chao Phraya River Estuary, Thailand. *Mar. Pollut. Bull.* **2020**, *161*, 111747. [CrossRef] [PubMed]
29. Lheknim, V. Fishes of Thale Noi and its tributaries, South Thailand. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *535*, 012042. [CrossRef]
30. Rittiboon, K.; Karntanut, W. Distribution of Resident birds in a protected tropical habitat in South Thailand. *J. Issaas* **2011**, *17*, 95–103.
31. US EPA. *QA/QC Guidance for Sampling and Analysis of Sediments, Water, and Tissues for Dredged for Material Evaluations*; EPA-823-B95-001; U.S. Environmental Protection Agency, Office of the Science Advisor: Washington, DC, USA, 1995; pp. 1–144.
32. Li, Y.; Zhou, H.; Gao, B.; Xu, D. Improved enrichment factor model for correcting and predicting the evaluation of heavy metals in sediments. *Sci. Total Environ.* **2021**, *755*, 142437. [CrossRef]
33. Hasan, A.B.; Selim Reza, A.H.M.; Kabir, S.; Siddique, M.A.B.; Ahsan, M.A.; Akbor, M.A. Accumulation and distribution of heavy metals in soil and food crops around the ship breaking area in southern Bangladesh and associated health risk assessment. *SN Appl. Sci.* **2020**, *2*, 155. [CrossRef]
34. Taylor, S.R.; McLennan, S.M. The geochemical evolution of the continental crust. *Rev. Geophys.* **1995**, *33*, 241–265. [CrossRef]
35. Shazili, N.A.M.; Rashid, M.K.A.; Husain, M.L.; Nordin, A.; Ali, S. Trace metals in the surface sediments of the South China Sea, area I: Gulf of Thailand and the East Coast of Peninsular Malaysia. In Proceedings of the First Technical Seminar on Marine Fishery Resources Survey in the South China Sea, Area I: Gulf of Thailand and East Coast of Peninsular Malaysia, Bangkok, Thailand, 24–26 November 1997; Training Department, Southeast Asian Fisheries Development Center: Bangkok, Thailand, 1999; pp. 73–85.
36. Ghrefat, H.A.; Abu-Rukah, Y.; Rosen, M.A. Application of geoaccumulation index and enrichment factor for assessing metal contamination in the sediments of Kafrain dam, Jordan. *Environ. Monit. Assess.* **2011**, *178*, 95–109. [CrossRef] [PubMed]
37. Ekissi, D.; Kinimo, K.C.; Kamelan, T.M.; Kouamelan, E.P. Physicochemical Characteristics and Heavy Metals Contamination Assessment in Water and Sediment in a Tropical Hydroelectric Dam of Sassandra River, Côte d'Ivoire. *J. Environ. Pollut. Hum. Health* **2021**, *9*, 27–35. [CrossRef]
38. Perumal, K.; Antony, J.; Muthuramalingam, S. Heavy metal pollutants and their spatial distribution in surface sediments from Thondi coast, Palk Bay, South India. *Environ. Sci. Eur.* **2021**, *33*, 63. [CrossRef]
39. Muller, G. Index of geoaccumulation in the sediments of the Rhine River. *GeoJournal* **1969**, *2*, 108–118.
40. Jiang, M.; Zeng, G.; Zhang, C.; Ma, X.; Chen, M.; Zhang, J.; Lu, L.; Yu, Q.; Hu, L.; Liu, L. Assessment of heavy metal contamination in the surrounding soils and surface sediments in Xiawangang River, Qingshuitang District. *PLoS ONE* **2013**, *8*, e71176. [CrossRef] [PubMed]
41. Salcedo Sánchez, E.R.; Martínez, J.M.E.; Morales, M.M.; Talavera Mendoza, O.; Alberich, M.V.E. Ecological and Health Risk Assessment of Potential Toxic Elements from a Mining Area (Water and Sediments): The San Juan-Taxco River System, Guerrero, Mexico. *Water* **2022**, *14*, 518. [CrossRef]
42. Hakanson, L. An ecological risk assessment index for aquatic contamination control, a sedimentological approach. *Water Res.* **1980**, *14*, 975–1001. [CrossRef]
43. Sowunmi, K.; Titilaya, S.; Sowanmi, L. Seasonal bioavailability of heavy metal contaminants from the university of Lagos lagoon, Nigeria. *Res. Sq.* **2020**, 1–8. [CrossRef]
44. Oluyemi, U.A.; Feuyit, G.; Oyekunle, J.A.O.; Ogunfowokan, A.O. Seasonal variations in heavy metal concentrations in soil and some selected crops at a landfill in Nigeria. *Afr. J. Environ. Sci. Technol.* **2008**, *2*, 089–096.
45. Pradit, S.; Gao, Y.; Faiboon, A.; Galan De, S.; Baeyens, W.; Leemaker, M. Application of DET (diffusive equilibrium in thin films) and DGT (diffusive gradients in thin films) techniques in the study of the mobility of sediment bound metals in the outer section of Songkhla Lake, southern Thailand. *Environ. Monit. Assess.* **2013**, *185*, 4207–4220. [CrossRef]
46. US EPA. *Guidance for the Pollution Classification of Great Lakes Harbor Sediments*; U.S. Environmental Protection Agency: Chicago, IL, USA, 1997; pp. 1–8.
47. MacDonald, D.D.; Ingersoll, C.G.; Berger, T.A. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Arch. Environ. Contam. Toxicol.* **2000**, *39*, 20–31. [CrossRef] [PubMed]
48. NOAA. Sediment Quality Guidelines Developed for the National Status and Trends Program. 1999. Available online: http://response.restoration.noaa.gov/book_shelf/121_sedi_qual_guide.pdf (accessed on 20 July 2010).
49. Sompongchaiyakul, P.; Sirinawin, W. Arsenic, chromium and mercury in surface sediment of Songkhla Lake system, Thailand. *Asian J. Water Environ. Pollut.* **2007**, *4*, 17–24.
50. Zhang, J.; Liu, C.L. Riverine composition and estuarine geochemistry of particulate metals in China-weathering features, anthropogenic impact and chemical fluxes. *Estuar. Coast. Shelf Sci.* **2002**, *54*, 1051–1070. [CrossRef]
51. Shrivastava, A.; Ghosh, D.; Dash, A.; Bose, S. Arsenic Contamination in Soil and Sediment in India: Sources, Effects, and Remediation. *Curr. Pollut. Rep.* **2015**, *1*, 35–46. [CrossRef]
52. Datta, R.; Sarkar, D. Arsenic geochemistry in three soils contaminated with sodium arsenite pesticide: An incubation study. *Environ. Geosci.* **2004**, *2*, 87–97. [CrossRef]

53. Armbrust, K.; Bridges, D.C. Dissipation of Monosodium Methane Arsonate (MSMA) on Peanuts. *J. Agric. Food Chem.* **2002**, *50*, 1959–1963. [CrossRef]
54. Quazi, S.; Datta, R.; Sarkar, D. Effects of soil types and forms of arsenical pesticide on rice growth and development. *Int. J. Environ. Sci. Technol.* **2011**, *8*, 445–460. [CrossRef]
55. Kljaković-Gašpić, Z.; Bogner, D.; Ujević, I. Trace metals (Cd, Pb, Cu, Zn and Ni) in sediment of the submarine pit Dragon ear (Soline Bay, Rogoznica, Croatia). *Environ. Geol.* **2008**, *58*, 751–760. [CrossRef]
56. Harikumar, P.S.; Nasir, U.P. Ecotoxicological impact assessment of heavy metals in core sediments of a tropical estuary. *Ecotoxicol. Environ. Saf.* **2010**, *73*, 1742–1747. [CrossRef] [PubMed]
57. Lari, B.; Egobueze, F.E.; Iwegbue, C.M.A.; Arimoro, F.O. Distribution of metals in sediment core of Orogodo river, Southern Nigeria. *FTSTJ* **2018**, *3*, 985–991.
58. Gao, C.; Yu, J.; Min, X.; Cheng, A.; Hong, R.; Zhang, L. Heavy metal concentrations in sediments from Xingyun lake, southwestern China: Implications for environmental changes and human activities. *Environ. Earth Sci.* **2018**, *77*, 666. [CrossRef]
59. Ruilian, Y.; Xing, Y.; Yuanhui, Z.; Gongren, H.; Xianglin, T. Heavy metal pollution in intertidal sediments from Quanzhou Bay, China. *J. Environ. Sci.* **2008**, *20*, 664–669.
60. Yang, G.; Song, Z.; Sun, X.; Chen, C.; Ke, S.; Zhang, J. Heavy metals of sediment cores in Dachan Bay and their responses to human activities. *Mar. Pollut. Bull.* **2020**, *150*, 110764. [CrossRef]
61. Zhuang, H.; Gao, M.; Yan, C.; Cao, Y.; Zhang, J. Vertical profiles and contamination assessments of heavy metals in sediment cores from typical intertidal zones in northern China. *Mar. Pollut. Bull.* **2020**, *159*, 111442. [CrossRef] [PubMed]
62. Shahabi-Ghahfarokhi, S.; Josefsson, S.; Apler, A.; Kalbitz, K.; Åström, M.; Ketzer, M. Baltic Sea sediments record anthropogenic loads of Cd, Pb, and Zn. *Environ. Sci. Pollut. Res.* **2021**, *28*, 6162–6175. [CrossRef]
63. Choi, S.C.; Wai, O.W.H.; Choi, T.W.H.; Li, X.D.; Tsang, C.W. Distribution of cadmium, chromium, copper, lead and zinc in marine sediments in Honk Kong waters. *Environ. Geol.* **2006**, *51*, 455–461. [CrossRef]