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# Metal distributions in the Kaohsiung Ocean dredged material disposal site, Taiwan

Chih-Feng Chen[a], Yun-Ru Ju[a], Chiu-Wen Chen[a], Yi-Kuo Chang[b], Cheng-Di Dong[a,c,*]

[a]*Department of Marine Environmental Engineering, National Kaohsiung Marine University, Kaohsiung 81157, Taiwan, Tel. +886-7-3617141-3762 (C.-F. Chen), +886-7-3617141-3765 (Y.-R. Ju), +886-7-3617141-3761 (C.-W. Chen), +886-7-3617141-3762 (C.-D. Dong); Fax: +886-7-365-0548; emails: dong3762@mail.nkmu.edu.tw (C.-F. Chen), yrju@webmail.nkmu.edu.tw (Y.-R. Ju), cwchen@mail.nkmu.edu.tw (C.-W. Chen), cddong@mail.nkmu.edu.tw (C.-D. Dong)*
[b]*Department of Safety Health and Environmental Engineering, Central Taiwan University of Science and Technology, Taichung 40601, Taiwan, Tel. +886-4-22391647-6858; email: ykchang@ctust.edu.tw*
[c]*Department of Bioinformatics and Medical Engineering, Asia University, Taichung 41354, Taiwan, Tel. +886-7-3617141-3762; Fax: +886-7-365-0548; email: cddong@mail.nkmu.edu.tw*

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**ABSTRACT**

This study compared the sediment characteristics, heavy metal content, enrichment factor (EF), geo-accumulation index ($I_{geo}$) and other heavy metal pollution indicators between the sediments inside and outside the Kaohsiung Ocean Dredged Material Disposal Site (KODMDS). The aim was to examine the impact of dumping harbor dredged sediments into the ocean on the heavy metal distribution in the sediments of KODMDS. The relatively significant variations were found in particle size distribution of the disposal site, whereas those of the outside disposal site were relatively stable. Results indicate that the organic and heavy metal content in the disposal site were significantly higher than those outside the disposal site. Compared with the sediments outside the disposal site, the heavy metal enrichment and accumulation level in the disposal site increased in the dredged sediments, especially the content of Cr, Cu, and Zn. According to the analysis results of the heavy metal pollution indicators, including: the pollution load index (PLI), mean effect range median quotient (m-ERM-q) and potential ecological risk index (RI), the level of heavy metal pollution, the potential eco-toxicity and the potential ecological risk of the sediments inside the disposal site all showed a slight increase albeit without significant impact on the benthos inhabiting the disposal site. The result also indicates that the content of heavy metal in the dredged sediments constitutes one of the major factors that account for the increased heavy metal content in the sediments of the disposal site. In addition, the method of dumping the dredged sediments and the environmental condition of KODMDS may be some of the reasons for the same level of heavy metal content in sediments from KODMDS, where dredged sediments have been dumped for 10 years, and from other sea areas without disposal of dredged sediments.

*Keywords:* Enrichment factor; Geo-accumulation index; Heavy metal; Kaohsiung Ocean Dredged Material Disposal Site (KODMDS); Sediment

## 1. Introduction

Sediments accumulate rapidly and in large amounts in harbors due to natural effects such as river scouring, surface runoff, and atmospheric deposition. In order to ensure the safety of ship sailing and berthing, it is necessary to implement dredging operations and dump dredged sediments into the ocean as the final disposal step, to maintain an adequate depth of fairways, berths, and docks of the harbor [1–4]. In the U.S., approximately $3 \times 10^8$ m$^3$ of dredged sediments are dumped into the ocean every year [2], while it is 40 million

* Corresponding author.

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tons (wet base) in the U.K. [5] and $1.5 \times 10^8$ m$^3$ [6] in China. As for Taiwan, there is only one ocean disposal site at present, where the dumped sediments mainly come from Kaohsiung Harbor. Since pollutants can be easily adsorbed and accumulated into dredged sediments, dumping such sediments into the ocean may impact the ecological environment of the disposal site [7,8].

Every year, 0.5 million m$^3$ of dredged sediments from Kaohsiung Harbor are dumped in the Kaohsiung Ocean Dredged Material Disposal Site (KODMDS) [7], which is 12 to 15 nm from the shore. After the fairway maintenance and dredging operation in Kaohsiung Harbor, KODMDS was established by the Taiwan Environmental Protection Agency (TWEPA) in 2003 as the disposal site of dredged sediments. Nowadays, certain regulations are established to manage the ocean dumping material in Taiwan. Material containing organohalogen compounds, mercury and mercury compounds, cadmium and cadmium compounds, persistent plastics, crude oil and its wastes, radioactive wastes, and in whatever form produced for biological and chemical warfare is prohibited to dump, belonging Class A. Material which has the relative low harm to the environments requires to apply the special permit to ocean dumping every time, belonging Class B. When the material is not the cases of Class A and B, it can be disposed within a given time and site after the permit of ocean dumping is certified. Since the industrial, municipal and agricultural sewage and wastewater from neighboring areas, as well as the water from four major polluted rivers (Love River, Canon River, Gen-Jen River and Salt River) all flow into Kaohsiung Harbor, the sediments in the Harbor exhibit high organic loading and heavy metal enrichment [8,9]. Therefore, the sediment in Kaohsiung Harbor is grouped to Class B. Despite the restricted permissible concentration of dredged sediments in the disposal site for ocean dumping, as well as the fact that the negative impact of dredged sediments on the water environment can be reduced by the dilution and diffusion effect of the ocean, the long-term ocean dumping of dredged sediments, may lead to the decreased quality of the sediments in the disposal site, especially in regard to the non-biodegradable heavy metals, in comparison with unpolluted disposal sites elsewhere. Consequently, it is necessary to examine the heavy metal distribution and enrichment level in the sediments of the disposal site, as well as their potential impact on the organisms after the ocean dumping. This study was conducted through on-site sampling and monitoring. The researchers of this study analyzed the physicochemical properties of the sediments inside and outside KODMDS to examine the heavy metal distribution in the sediments of the disposal site, and then assessed the changes of the heavy metal content, enrichment and geo-accumulation level after the ocean dumping, in addition to their potential impact on the ecology.

## 2. Materials and methods

### 2.1. Study area and sampling

KODMDS is located 12 to 15 nm from the shore. The disposal site is centered at E120°03.59′, N22°27.57′, and covers a 36 km$^2$ area with a side length of 6 km and a depth between 500 and 700 m (Fig. 1). As the exclusive dredged

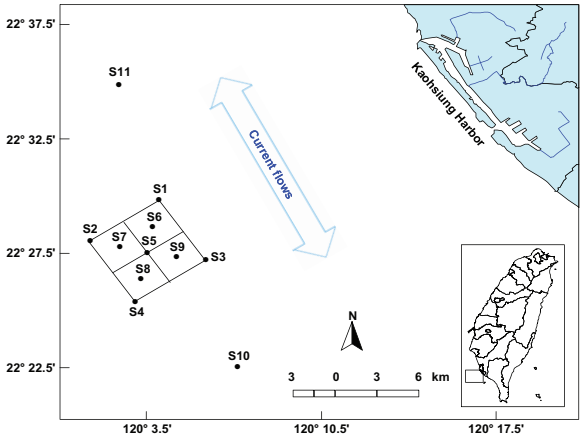


Fig. 1. Map of the study area and sampling locations.

sediment disposal site for Kaohsiung Harbor since 2003, KODMDS receives 500 thousand m$^3$ of dredged sediments from Kaohsiung Harbor every year, and had accumulated 4.69 million m$^3$ of dredged sediments by 2013. The disposal site is divided into four disposed areas which receive ocean dumping in turn; a maximum of 15 thousand m$^3$ of dredged sediments are allowed to be dumped into each disposed area in turn for ocean dumping [10]. The researchers of this study set up nine sites, including the four disposed area vertex angles (S1 – S4), the center (S5) and the disposed area centers (S6 – S9), where the ocean dumping is conducted. In addition, since the neighboring sea current is mainly in the southeast and northwest direction according to the past data on sea currents, two reference sites were also set up at the south (S10) and the north (S11) of the disposal site, respectively (Fig. 1). Based on the locations of the sites and the dredged sediment disposed areas, the sites are grouped into three larger areas, which are Area I: the disposed area centers (S6 – S9), Area II: disposed area vertex angles (S1 – S4) and Area R: outer disposal site (S10 and S11). The operation of the sampling in the sites within KODMDS was implemented by a research vessel, Ocean Researcher III, in March, May, July, and October in 2013. The surface sediment samples were collected by a Shipek sediment sampler. The researchers collected 3 kg of surface sediments at each site, and the collected sediments were placed immediately in polybags and stored in a refrigerator at –4°C until they were sent to the lab.

### 2.2. Sample preparation and analysis

When the sediment samples were sent to the lab, wet screening was performed with 1 mm nylon mesh size to eliminate particles more than 1 mm in diameter. After the wet screening, part of the samples was selected to perform a particle size distribution analysis with a Coulter LS230 particle size analyzer [11]. The range of the particle size distribution was divided into three categories: clay (<2 μm in diameter), silt (2–63 μm in diameter), and sand (>63 μm in diameter) [12]. The other samples were placed in a dark area for natural drying, after which they were ground into fine particles with a zirconia mortar and pestle, put into an acid cleaned plastic bottle and stored in the freezer at –20°C. The organic matter (OM) in the samples was analyzed with the loss-on-ignition

(LOI) method [11]. The procedures of the analysis of Al and six other trace heavy metals (Hg, Cd, Cr, Cu, Pb, Zn, and Ni) content was as follows: 2.000 g of the samples were taken out and mixed with ultra-pure acid ($HNO_3$:HCl:HF = 5:2:5, *V*/*V*/*V*). The mixture was then digested by a microwave digester (MARS 5, CEM, USA). After that, the digested fluid was screened with 0.45 μm filter papers, and the filtrate was diluted with ultrapure water to 15 mL. The concentration of heavy metals in the digested fluid (Pb, Cd, Cr, Cu, Zn, Ni, and Al) was then analyzed with a flame atomic absorption spectrophotometer (Hitachi Z-6000, Japan). The analysis of the concentration of Hg in the digested fluid was performed with the MHS-10 technique (USEPA Method 7471A) [13]. Every batch of the analysis was accompanied with a standard reference matter (marine sediment reference materials for trace metals (PACS-2)) and a blank sample. The standard solution was also adopted to check the stability of the measuring instruments after every 10 batches of analysis were conducted. In this study, the difference of the assay and certified values of heavy metals of measured PACS-2 is less than 10% in both. The measured values of the heavy metals in the blank samples are all lower than the detection limit value. The sample recovery rate is between 91.5% and 108.3%. The detection limit values of Al, Hg, Pb, Cd, Cr, Cu, Zn, and Ni are, respectively, 5, 0.01, 0.1, 0.03, 0.1, 0.5, 0.5, and 0.1 mg $kg^{-1}$ (dry weight).

### 2.3. Data analysis

The data on the sediment samples were examined via statistical analysis, including maximum value, minimum value, mean value, and standard deviation. One-way ANOVA was performed to examine the characteristics of the sediments from different areas (I, II, and R), as well as the average deviation of their heavy metal content; the *F*-test was employed to examine the variance of measured values in each area. The enrichment and the geo-accumulation level of the heavy metals in the sediment were assessed by the enrichment factor (EF) and geo-accumulation index ($I_{geo}$). In addition, the overall pollution level of heavy metals, the biological effects and the potential ecological risk were assessed by the pollution load index (PLI) [14], mean effect range median quotient (m-ERM-q) [15] and potential ecological RI [16]. All of the calculation equations of the assessment methods in this study are described as follows.

The EF is an assessment method for normalizing heavy metal content based on the geological characteristics of sediments; it is generally defined as the ratio of the heavy metals and background heavy metals in the sediment samples normalized by Al. The calculation formula is as follows:

$$EF = \frac{(C_m / C_{A1})}{B_m / B_{A1})} \tag{1}$$

where ($C_m/C_{Al}$) represents the ratio of the sediment and Al concentration, while ($B_m/B_{Al}$) represents the ratio of the background heavy metals and Al concentration. Al is one of the major metallic elements in the Earth's crust, and its concentration in the sediments reaches a certain high level; thus, it is not subject to the influence of anthropogenic factors, and is generally adopted in the normalization of metal concentration in sediments. In this study, the background values of the heavy metals are calculated using the mean concentrations of the earth's crust [17]: Hg = 0.08, Cd = 0.2, Cr = 100, Cu = 55, Ni = 75, Pb = 12.5, Zn = 70 mg $kg^{-1}$, and Al = 8.23%. When the EF value is greater than 1, it means the heavy metals come from anthropogenic (human) activities. Conversely, when the EF value is less than 1, it means the heavy metals are formed by natural (nonhuman) processes [8–9,18]. Furthermore, the EF value can be divided into seven classes of enrichment [19]: 1, no enrichment for EF < 1; 2, minor for 1 < EF < 3; 3, moderate for 3 ≤ EF < 5; 4, moderately severe for 5 ≤ EF < 10; 5, severe for 10 ≤ EF < 25; 6, very severe for 25 ≤ EF < 50; and 7, extremely severe for EF ≥50.

The geo-accumulation index ($I_{geo}$) was proposed by Müller [20] as a reference when assessing the geo-accumulation levels of the heavy metals in sediments. The calculation formula is as follows:

$$I_{geo} = \log_2\left(\frac{C_m}{1.5B_m}\right) \tag{2}$$

where $C_m$ represents the heavy metal concentration in the sediments, $B_m$ represents the background heavy metal concentration and 1.5 is the factor compensating the background data (i.e., the correction factor) due to the lithogenic effects. The $I_{geo}$ value can be divided into seven classes of geo-accumulation [20]: 0, none for $I_{geo}$ <0; 1, none to medium for $I_{geo}$ = 0–1; 2, moderate for $I_{geo}$ = 1–2; 3, moderately strong for $I_{geo}$ = 2–3; 4, strong for $I_{geo}$ = 3–4; 5, strong to very strong for $I_{geo}$ = 4–5; and 6, very strong for $I_{geo}$ >5.

The PLI is a comprehensive assessment of the heavy metals pollution level. The calculation formula is as follows [14]:

$$PLI = \sqrt[n]{CF_1 \times CF_2 \times CF_3 \cdots \times CF_n} \tag{3}$$

where *CF* refers to the Contamination Factor, which is $C_m/B_m$; *n* is the number of heavy metals examined. PLI can assess the overall status of heavy metal pollution, or compare the pollution status among different areas. When PLI ≥1, it means the sediments have been polluted by heavy metals; conversely, when PLI <1, it means the sediments are not polluted [14].

The mean effect range median quotient (m-ERM-q) was proposed by Long et al. [15]. The calculation formula is as follows:

$$m-\mathrm{ERM}-q = \frac{\sum(\mathrm{ERMQ}_m)}{n} = \frac{\sum(C_m / \mathrm{ERM}_m)}{n} \tag{4}$$

where $ERM_m$ represents the effect range median (ERM) values corresponding to the heavy metals: Hg = 0.71 mg $kg^{-1}$, Cd = 9.6 mg $kg^{-1}$, Cr = 370 mg $kg^{-1}$, Cu = 270 mg $kg^{-1}$, Pb = 218 mg $kg^{-1}$, and Zn = 410 mg $kg^{-1}$ [21], with n signifying the number of examined heavy metals. By calculating the mean quotients of each examined heavy metal, m-ERM-q can assess the potential biological effect of multiple heavy metals [9,22]. According to the calculated m-ERM-q, the potential

toxicity of the heavy metals in sediments can be divided into four classes [23]: m-ERM-q <0.1 (12% probability of toxicity), 0.11–0.5 (30% probability of toxicity); 0.51–1.5 (46% probability of toxicity); and >1.5 (74% probability of toxicity).

The potential ecological RI is a quantitative method for ecological risk proposed by Hakanson [16]. The calculation formula is as follows:

$$\mathrm{RI} = \sum \mathrm{Er}_m = \sum PI \times T_m = \sum \left( \frac{C_m}{B_m} \right) \times T_m \quad (5)$$

where $\mathrm{Er}_m$ represents a potential ecological risk factor of a single heavy metal, *PI* represents the pollution index and $T_m$ represents the biological toxicity factor, that is, Hg = 40, Cd = 30, Cr = 2, Cu = Ni = Pb = 5, and Zn=1 [16,24]. The *RI* method covers various fields: bio-toxicology, environmental chemistry, and eco-environment, and can assess the overall ecological risk caused by heavy metals. According to the suggestion proposed by Hakanson [16], the RI value can be divided into the following classes: RI<150 for low ecological risk; 150 ≤ RI < 300 for moderate ecological risk; 300 ≤ RI < 600 for considerable ecological risk; and RI ≥ 600 for very high ecological risk.

Table 1
Location, water depth, and basic characteristics of the surface sediments of KODMDS (mean ± standard deviation)

| Area[a] | Site | Longitude (East) | Latitude (North) | Water depth (m) | Organic matter (%) | Clay (<2 μm) (%) | Silt (2–63 μm) (%) | Sand (>63 μm) (%) |
|---|---|---|---|---|---|---|---|---|
| I | S6 | 120° 03.95′ | 22° 28.82′ | 566 | 4.1 ± 1.1 | 14.0 ± 8.8 | 59.9 ± 30.0 | 26.2 ± 37.1 |
| | S7 | 120° 02.51′ | 22° 27.88′ | 716 | 4.2 ± 0.9 | 12.5 ± 7.8 | 61.8 ± 25.8 | 25.7 ± 32.9 |
| | S8 | 120° 03.48′ | 22° 26.50′ | 631 | 4.1 ± 0.5 | 15.7 ± 7.6 | 68.5 ± 13.7 | 15.8 ± 19.6 |
| | S9 | 120° 04.98′ | 22° 27.44′ | 592 | 4.4 ± 0.9 | 8.5 ± 4.5 | 46.6 ± 28.0 | 44.9 ± 32.3 |
| II | S1 | 120° 04.30′ | 22° 30.06′ | 571 | 4.4 ± 0.5 | 17.1 ± 8.0 | 70.9 ± 5.0 | 12.0 ± 12.2 |
| | S2 | 120° 01.42′ | 22° 28.18′ | 629 | 4.2 ± 0.8 | 19.0 ± 4.3 | 73.9 ± 6.6 | 7.0 ± 7.6 |
| | S3 | 120° 06.36′ | 22° 27.31′ | 539 | 4.3 ± 0.3 | 19.1 ± 5.8 | 77.1 ± 4.6 | 3.8 ± 5.3 |
| | S4 | 120° 03.36′ | 22° 25.42′ | 723 | 4.8 ± 0.4 | 19.6 ± 7.5 | 79.1 ± 8.7 | 1.3 ± 1.8 |
| | S5 | 120° 03.59′ | 22° 27.57′ | 602 | 3.6 ± 0.3 | 10.6 ± 7.4 | 52.2 ± 33.9 | 37.2 ± 41.2 |
| R | S10 | 120° 07.48′ | 22° 23.00′ | 667 | 4.6 ± 0.3 | 18.3 ± 1.3 | 80.7 ± 2.3 | 1.0 ± 1.2 |
| | S11 | 120° 02.45′ | 22° 34.77′ | 431 | 3.3 ± 0.6 | 15.6 ± 2.9 | 73.5 ± 8.6 | 10.9 ± 10.8 |

[a]I, disposed area centers; II, disposed area vertex angle; and R, outer disposal site.

Table 2
Concentration (mg $kg^{-1}$ dry weight) of metals in the surface sediment of KODMDS (mean ± standard deviation)

| Area[a] | Site | Hg | Pb | Cd | Cr | Cu | Zn | Ni | Al |
|---|---|---|---|---|---|---|---|---|---|
| I | S6 | 0.43 ± 0.06 | 19.3 ± 4.3 | 0.15 ± 0.06 | 37.5 ± 18.0 | 27.7 ± 10.6 | 153.0 ± 61.0 | 28.2 ± 4.1 | 5.08 ± 0.60 |
| | S7 | 0.41 ± 0.05 | 15.2 ± 3.8 | 0.18 ± 0.05 | 30.6 ± 13.8 | 17.7 ± 5.8 | 120.0 ± 33.2 | 21.5 ± 2.8 | 5.18 ± 0.38 |
| | S8 | 0.47 ± 0.09 | 19.3 ± 1.7 | 0.19 ± 0.09 | 34.7 ± 16.9 | 25.0 ± 5.6 | 131.0 ± 40.3 | 26.2 ± 5.5 | 5.09 ± 0.33 |
| | S9 | 0.42 ± 0.09 | 16.8 ± 3.3 | 0.21 ± 0.09 | 36.0 ± 19.0 | 19.2 ± 6.0 | 131.1 ± 82.3 | 24.0 ± 4.3 | 5.38 ± 0.38 |
| II | S1 | 0.37 ± 0.06 | 14.3 ± 3.1 | 0.19 ± 0.06 | 27.7 ± 11.1 | 21.1 ± 7.3 | 136.7 ± 49.4 | 19.9 ± 4.3 | 5.19 ± 0.47 |
| | S2 | 0.34 ± 0.08 | 19.5 ± 7.5 | 0.20 ± 0.08 | 83.2 ± 58.0 | 42.0 ± 27.9 | 158.1 ± 46.9 | 25.3 ± 8.6 | 5.14 ± 0.45 |
| | S3 | 0.35 ± 0.09 | 16.4 ± 2.7 | 0.20 ± 0.09 | 34.8 ± 11.2 | 30.5 ± 15.1 | 145.6 ± 15.4 | 22.4 ± 5.2 | 5.22 ± 0.49 |
| | S4 | 0.35 ± 0.03 | 16.3 ± 3.4 | 0.14 ± 0.03 | 41.7 ± 7.2 | 32.8 ± 9.8 | 147.0 ± 73.5 | 23.2 ± 6.0 | 5.09 ± 0.40 |
| | S5 | 0.37 ± 0.06 | 15.5 ± 4.0 | 0.18 ± 0.06 | 70.6 ± 48.7 | 26.9 ± 10.4 | 174.9 ± 50.5 | 21.3 ± 5.2 | 4.88 ± 0.19 |
| R | S10 | 0.35 ± 0.06 | 19.7 ± 3.6 | 0.20 ± 0.06 | 34.7 ± 14.5 | 22.1 ± 8.6 | 142.0 ± 56.8 | 26.6 ± 5.12.5 | 5.18 ± 0.23 |
| | S11 | 0.29 ± 0.05 | 11.4 ± 1.2 | 0.18 ± 0.05 | 23.2 ± 10.1 | 10.0 ± 2.5 | 68.3 ± 35.3 | 17.8 ± | 4.77 ± 0.40 |
| ERL[b] | | 0.15 | 46.7 | 1.2 | 81 | 34 | 150 | 20.9 | – |
| ERM[b] | | 0.71 | 218 | 9.6 | 370 | 270 | 410 | 51.6 | – |

[a]I, disposed area centers; II, disposed area vertex angle; and R, outer disposal site.
[b]ERL and ERM present the effect range low and median [21].

## 3. Results and discussion

### 3.1. Effect on sediment characteristics and metal concentrations

Table 1 shows the content and particle size distribution of organic matter (OM) in the surface sediments from KODMDS. The mean OM values of the sediment samples from all the sites fall between 3.3% and 4.8%. There are no significant differences found in the mean values (ANOVA test, $p > 0.05$) and the variances ($F$-test, $p > 0.05$) of the disposed area centers (Area I), disposed area vertex angles (Area II) and outer disposal site (Area R). The percentages of the clay, silt and sand of the sediments fall between 8.5%–19.6%, 46.6%–80.7%, and 1.0%–44.9%, respectively, meaning silt is the main component of the sediments. No significant difference is found in the mean values of the clay, silt, and sand in Areas I, II, and R (ANOVA test, $p > 0.05$); however, the composition variances of the clay ($F$-test, $p < 0.01$), silt ($F$-test, $p < 0.01$), and sand ($F$-test, $p < 0.01$) of Areas I, II, and R differ significantly, indicating that the variances may be related to the properties of the dredged sediments. The change of the particle sizes of the sediments in KODMDS may cause the change of dominant species of the benthos inhabiting the disposal site [3].

The distributions of heavy metals in the sediment samples of all the sites from KODMDS are listed in Table 2. The average content of Hg, Pb, Cd, Cr, Cu, Zn, and Ni in the sediment samples of every site fall between 0.29–0.47 mg $kg^{-1}$ dw, 11.4–19.7 mg $kg^{-1}$ dw, 0.14–0.21 mg $kg^{-1}$ dw, 23.2–83.2 mg $kg^{-1}$ dw, 10.0–42.0 mg $kg^{-1}$ dw, 68.3– 174.9 mg $kg^{-1}$ dw, and 17.8– 28.4 mg $kg^{-1}$ dw, respectively. Among these data, Zn shows the highest geo-accumulation index, with Cd as the lowest. Fig. 2 shows the average content distribution of seven trace heavy metals and Al in the center of the disposal areas (Area I), disposed area vertex angles (Area II) and the outer disposal site (Area R) in this study. The average content of each heavy metal in Areas I and II is higher than those in Area R, and the average concentrations of *Cr* (ANOVA test, $p < 0.05$), Cu ($p < 0.05$), and Zn ($p < 0.05$) in Area I, as well as *Cu* ($p < 0.01$), and Zn ($p < 0.05$), are higher than those in Area R. The data indicate that the surface sediments in KODMDS may be impacted by the disposal of dredged sediments. Compared with the Sediment Quality Guidelines [21], only the content of the *Hg* in the sediments of KODMDS exceeds 0.15 mg $kg^{-1}$ over the Effect Range Low (ERL), while the six other heavy metals content is lower than the ERL. This indicates that the probability for contamination of the heavy metals in sediments of KODMDS impacting the benthos inhabiting the disposal site are quite low [21].

Kim et al. [25] monitored the sediments from the Ocean Waste Disposal Site in the Yellow Sea, South Korea (1988–2005). The results indicated slight impacts of the waste disposal on the average particle sizes, OMs and some trace minerals of the sediments in the disposal site, while the heavy metal content in certain sites exhibited an abnormal increase. In addition, according to a long-term monitoring data at the San Francisco Deep Ocean Disposal Site (SF-DODS), although the heavy metal concentration in the sediments of the disposal site increases slightly, the impact on the organism remains low [4]. The data shown in Table 3 indicate that the heavy metal concentration of the sediments in KODMDS is still five times lower than that of the sediments in Kaohsiung Harbor after 10 years of ocean dumping. The heavy metal content of the sediments in KODMDS is the same as those of sediments in other Asian sea areas (Table 3). Such results may be due to the fact that the dredged sediments had been

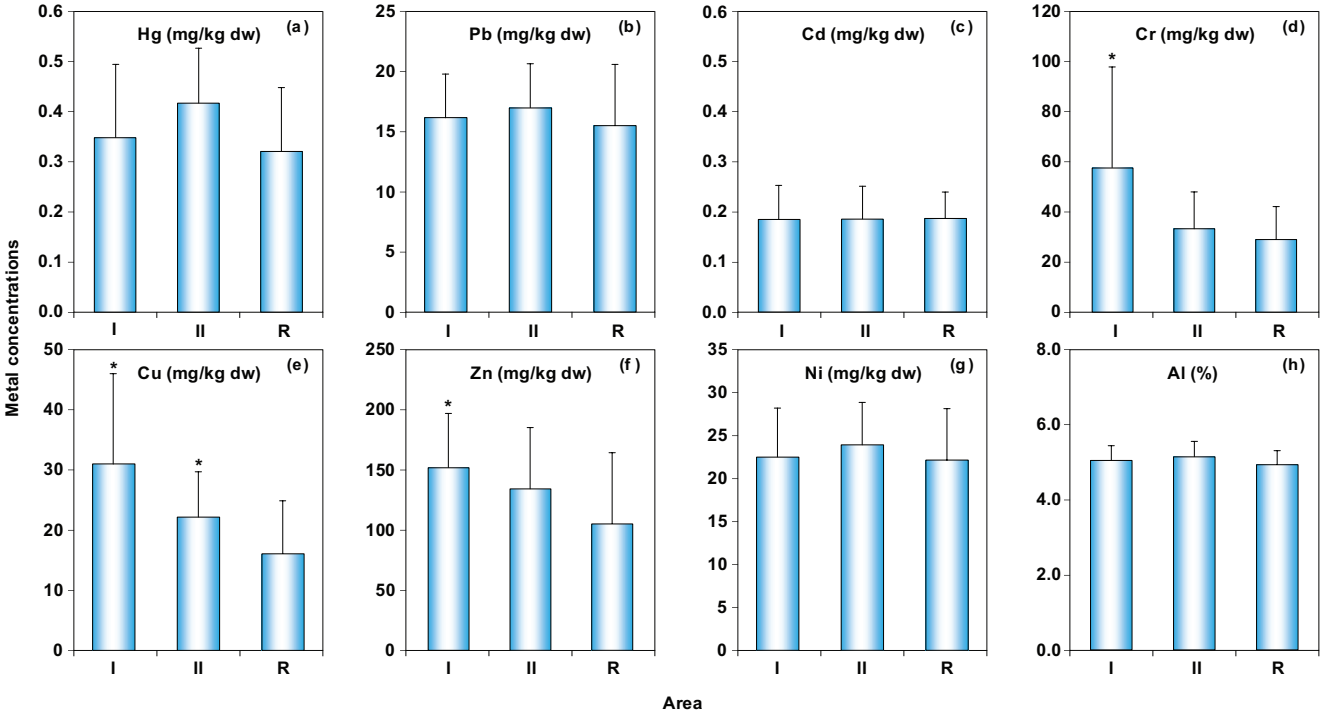


Fig. 2. Spatial distribution of metal content in the surface sediment of KODMDS. Area I: disposed area center, II: disposed area vertex angle, and R: outer disposal site.

Table 3
Metal concentration (mg kg$^{-1}$ dry weight) of marine sediments in different regions

| Location | Hg | Pb | Cd | Cr | Cu | Zn | Ni | References |
|---|---|---|---|---|---|---|---|---|
| KODMDS, Taiwan | 0.10–0.56 | 10.1–27.7 | 0.09–0.31 | 11.1–146.0 | 6.4–68.6 | 38.9–245 | 13.3–34.9 | Present study |
| Kaohsiung Harbor, Taiwan | 0.15–1.12 | 16–109 | 0.15–1.11 | 23–523 | 10–562 | 70–1,602 | – | [9] |
| Kaohsiung Coast, Taiwan | – | 2.5–23.8 | 0.05–0.42 | 12.5–95.0 | 1.3–23.8 | 45.0–127.5 | 3.8–42.5 | [26] |
| North Yellow Sea, China | – | 17–44 | 0.02–0.31 | 11–113 | 3–56 | 15–125 | – | [27] |
| East China Sea, China | – | 10.0–44.8 | – | – | 4.29–41.5 | 18.2–114.2 | 8.17–48.6 | [28] |
| Xiamen Bay, China | – | 44.9–59.8 | 0.11–1.01 | 36.7–134.3 | 18.5–97.2 | 65–223 | 24.8–64.8 | [29] |
| Quanzhou Bay, China | 0.17–0.74 | 34.3–100.9 | 0.28–0.89 | 51.1–121.7 | 24.8–119.7 | 105.5–241.9 | 16.1–45.7 | [30] |
| Tianjin Bohai Bay, China | 0.02–0.85 | 17.5–34.9 | 0.14–1.82 | 18–191 | 11.4–27.3 | 68.7–392.8 | – | [31] |
| Eastern Coast of the Gulf of Tailand | 0.005–0.121 | 1.69–66.3 | <0.006–0.19 | – | 14.4–103 | 7.48–131 | <0.64–80 | [32] |
| Korea Coast, Korea | ND–0.63 | 1.9–107 | ND–1.97 | 0.8–223 | 0.4–125 | 6–452 | – | [33] |
| Youngil Bay, Korea | – | 22.0–53.2 | 0.3–4.0 | 15.0–39.2 | 10.9–133.7 | 86.6–377.0 | – | [34] |
| Masan Bay, Korea | – | 13.0–82.2 | 0.1–7.5 | 30.5–99.8 | 13.5–90.7 | 80.0–378.7 | 10.2–40.4 | [35] |
| Hokkaido, Japan | 0.01–0.50 | 0.8–80 | 0.01–0.71 | 6–336 | 3–206 | 12–200 | – | [36] |
| Ise-Tokai region, Japan | – | 6.26–82.7 | 0.06–1.48 | 43.0–168 | 13.5–81.6 | 66.7–210 | 21.0–124 | [37] |

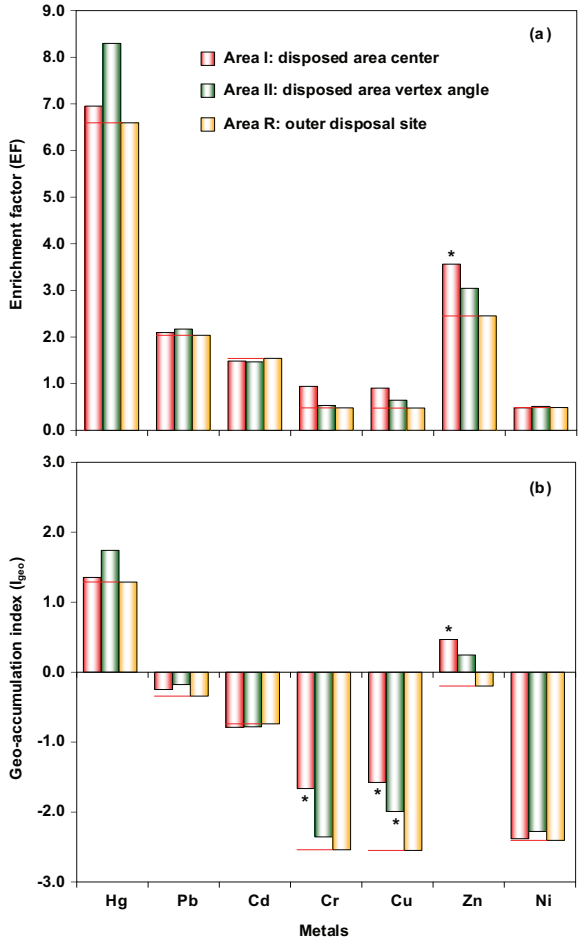


Fig. 3. Distribution of EF (a) and $I_{geo}$ (b) for seven metals in the surface sediment of KODMDS. Dashed line are the values of Area R.

diffused rapidly by strong sea streams, or that the dredged sediments were constantly mixed with fresh sea water, releasing the heavy metals inside while descending (the depth of KODMDS to between 500 and 700 m).

### 3.2. Effect on metal enrichment and geo-accumulation

EF and $I_{geo}$ are generally considered as the reference while assessing the enrichment and geo-accumulation of heavy metals in sediments [38]. Fig. 3 indicates the EF and $I_{geo}$ values of the heavy metals in the sediments of the three areas (Areas I, II and R) in KODMDS. The mean EF values of Hg, Pb, Cd, and Zn in all three areas are more than 1 (Fig. 3(a)), meaning these heavy metals exhibit the enrichment effects compared with the Earth's crust background values. According to the EF classification proposed by Birth [19], since the EF values of Cr, Cu, and Ni in the sediments of Areas I, II, and R are less than 1, they belong to EF Class 1 (no enrichment); the EF values of Pb and Cd are between 1 and 3, and thus belong to EF Class 2 (minor enrichment); the EF values of Zn in the sediments of Areas I and II are between 3 and 5, and thus belong to EF Class 3 (moderate enrichment); and the EF value of Zn in the sediments of Area R is 2.5, and thus belong to EF Class 2. Although the heavy metal concentrations of Cu and Cr in the disposed area centers (Area I) are significantly higher than those of the outer disposal site (Area R) (Fig. 2), they have not caused any enrichment effect perhaps because of the difference between the background values of the heavy metals of the sediments in the disposal site and those of the Earth's crust. Consequently, the data were examined based on the EF values of Area R; it was found that the EF values of all the heavy metals, except Cd, in Areas I and II are relatively higher than those in Area R, and the EF value of Zn in Area I is significantly ($p < 0.05$) higher than that in Area R (Fig. 3(a)), meaning the EF values of the heavy metals in the sediments of Areas I and II increase due to the disposal of dredged sediments, especially Zn.

Fig. 3(b) indicates that the mean $I_{geo}$ values of Pb, Cd, Cr, Cu, and Ni in Areas I, II, and R are less than 0, meaning they belong to $I_{geo}$ Class 0 (uncontaminated); the mean $I_{geo}$ values of Hg in Areas I, II, and R are between 1 and 2, meaning they belong to $I_{geo}$ Class 2 (moderately contaminated); the mean $I_{geo}$ values of Zn in Areas I and II are between 0 and 1, meaning they belong to $I_{geo}$ Class 1 (uncontaminated to moderately contaminated); and the mean $I_{geo}$ value of Zn in Area R is less than 0, meaning it belongs to $I_{geo}$ Class 0 (uncontaminated). Compared with the $I_{geo}$ values of Area R, it was found that the $I_{geo}$ values of all the heavy metals, except Cd, in Areas I and II are relatively higher than those in Area R, and the $I_{geo}$ values of Cr, Cu and Zn in Area I and the $I_{geo}$ values of Cu in Area II are significantly ($p < 0.05$) higher than those in Area R (Fig. 3(b)). According to the analysis results, the disposal of the dredged sediments in KODMDS may cause the geo-accumulation and enrichment effects of certain heavy metals (Cu, Cr, and Zn). It should be noted that the content of Cu, Cr, and Zn is the three metals with the highest content in the dredged sediments of Kaohsiung Harbor (Table 2), indicating that the content of heavy metals in the dredged sediments dumped into the ocean is one of the major factors accounting for the increased heavy metal content in the sediments of the disposal site.

### 3.3. Comprehensive effect assessment of heavy metal

According to the heavy metal concentration, EF values and $I_{geo}$ values of the sediments, the sediments in the disposal site may have been affected by the disposal of dredged sediments; thus, the heavy metals of the sediments in the disposal site increased in comparison to those outside the disposal site. Consequently, this study assessed the overall impacts of the seven heavy metals on the sediments using the PLI, m-ERM-q and RI analysis methods. The data shown in Fig. 4 (a) indicate that the PLI values of Area I (PLI = 1.01) and II (PLI = 0.92) are relatively higher than those of Area R (PLI = 0.78). In addition, since the PLI value of Area I is more than 1, the result indicates that Area I was polluted by heavy metals [14]. Although the PLI value in Area II is higher than in Area R, Area II was not polluted by heavy metals since the value of Area II is less than 1. Compared with those of Area R, Hg, Cu, Cr, and Zn in Areas I and II is the major heavy metal content responsible for the increased PLI values (Fig. 4(a)). The mean distributions of m-ERM-q values in Areas I, II, and R are similar to those of their PLI values: Area I (0.237) > Area II (0.236) > Area R (0.195) (Fig. 4(b)). The probability of toxicity for sediments of all three areas are ranked at the medium and low levels (30% probability of toxicity) [23]. As with the PLI values, Hg, Cu, Cr, and Zn in Areas I and II is the major heavy metal content responsible for the increased m-ERM-q values (Fig. 4(b)). The data shown in Fig. 4(c) indicate the potential ecological risks in these three areas. The RI value of Area II is the highest (RI = 250), followed by Area I (RI = 216), with Area R being the lowest (RI = 200), all of which belong to the level of moderate ecological risk (150 ≤ RI <300) [16].

In conclusion, after 10 years of ocean dumping, the level of heavy metal pollution, potential ecological toxicity and risk of KODMDS have slightly increased. However, the slight increase may not significantly impact the benthos inhabiting the disposal site. According to the long-term monitoring results of SF-DODS conducted by James et al. [3], the benthos inhabiting the disposal site are not impacted by the dredged sediments; both their abundance and diversity remain high. Nevertheless, since the particle size distribution varies with the dredged sediment characteristics, the dominant species also changes every year. Such an effect is in agreement with the research result of Charleston Ocean Dredged Material Disposal Site conducted by Zimmerman et al. [1]. The change in the biological community of the benthos inhabiting the disposal site results from the changed particle size distribution of the sediments, rather than from pollution. The change of the particle size distribution of the sediments in KODMDS was another finding of this study; such a change may account for the difference of dominant species of the benthic infauna in KODMDS.

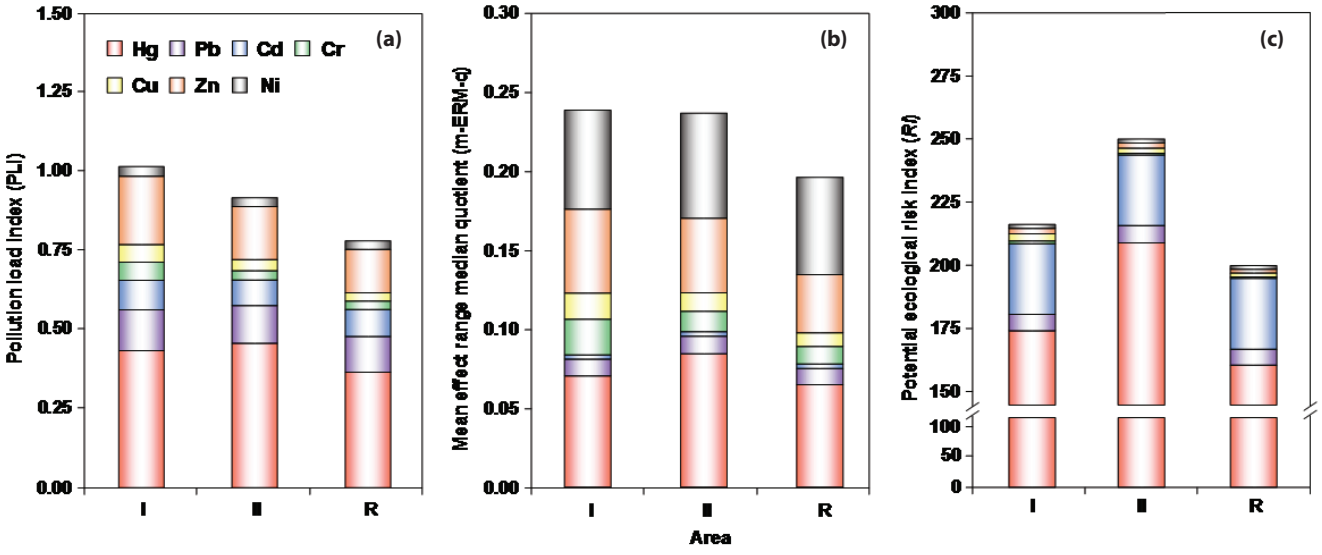


Fig. 4. Distribution of PLI (a), m-ERM-q (b), and RI (c) and the contribution of each metal in the surface sediment of KODMDS.

## 4. Conclusions

By comparing the particle size distributions, OM and heavy metal content between the sediments inside and outside KODMDS, it is noted that the disposal site was slightly impacted by the dredged sediments, such as in the change of particle size distribution, as well as the slight increase of heavy metal content. In addition, the results of the analysis with different indices, including EF, $I_{geo}$, PLI, m-ERM-q, and RI, the enrichment and geo-accumulation of the sediments in the disposal site slightly increased compared with those outside the disposal site, but the increase may not cause changes in the ecological toxicity and risk levels. The content of the heavy metals in the dredged sediments constitutes one of the major factors accounting for the increased heavy metal content in the sediments of the disposal site. Furthermore, it should be noted that the method of dumping dredged sediments into different disposed areas in turn, as well as the environmental condition of the disposal site (current flows and water depth) may involve other factors accounting for the decreased impact of dumping dredged sediments on the heavy metals in the sediments of the disposal site. This may be one of the important reasons why the heavy metal content of the 10-year-old KODMDS remains the same as those in other sea areas without disposal of dredged sediments.

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