

Spatial Distribution and Integrated Assessment of Heavy Metal Pollution using Different Indices in Marine Sediments of Abu Dhabi Waters and Management Strategies.

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ABSTRACT

Coastal pollution is a significant and growing concern in the Arabian Gulf waters due to discharges from desalination and sewage treatment facilities, reclamation and dredging operations, island development, and oil and natural gas exploration and extraction. To assess and manage the heavy metal pollution in Abu Dhabi's territorial waters, the Environment Agency – Abu Dhabi (EAD) collected surface sediment samples from 106 sites during 2015. The samples were analyzed for selected heavy metals and observed concentrations were found to be lower than the threshold limits proposed by international organizations. Moreover, the analysis of the data employing enrichment factor, geo-accumulation factor, contamination factor, pollution load index, and various statistical methods indicated that concentrations were below the threshold limits and anthropogenic inputs were limited. However, the increasing concentrations of some metals highlighted the need to control the discharges of heavy metals into the marine environment. This study discusses various efforts of EAD on heavy metal pollution abatement and highlights its management strategy, including recent policies and regulations. Furthermore, the results emphasize the critical need for a holistic approach and developing a comprehensive strategy to manage both local and trans-boundary heavy metal pollution.

Keywords: Heavy metals, enrichment factor, geo-accumulation index, principal component analysis

1 Introduction

Abu Dhabi is one of the seven emirates of the United Arab Emirates (UAE), situated in the southern Arabian Gulf. Over the past 50 years, Abu Dhabi has urbanized due to rapid economic, social, and industrial growth and development, which has in turn increased anthropogenic impacts on its marine environment, including heavy metals. Heavy metal pollution is one of the most serious threats to the marine environment due to the toxicity, persistence, and bioaccumulation of metals (Balachandran et al., 2005^[14]; Caeiro et al., 2005^[16]; Tam and Wong 2000^[56]; Al Rashdi et al., 2015^[5]; El Tokhi et al., 2017^[22]). In general, marine sediments act as a sink for heavy metal pollutants and play a vital role in monitoring and assessing heavy metal pollution. They can accumulate and assimilate heavy metals even from low concentrations in the overlying water column (Tam and Wong, 2000^[56]; Tan et al., 2016^[57]; El Nemr et al., 2007^[20]).

Abu Dhabi waters have been the subject of many environmental investigations, including heavy metal distribution. However, information on heavy metal distribution in Abu Dhabi waters, particularly offshore spatial distribution, is very limited. The spatial distribution of heavy metals in marine sediments is of major importance in determining the pollution history of the aquatic system (Birch, 2001^[15]; Sollitto, 2010^[54]). Moreover, it provides basic information to identify possible sources of

contamination, delineate areas where concentrations exceed threshold values, and develop strategies for site remediation (Sollitto, 2010^[54]). Therefore, understanding the mechanisms of accumulation and geochemical distribution of heavy metals in sediments is crucial for managing the coastal environment. The present study aims to determine the spatial distribution of heavy metals in the sediments of Abu Dhabi waters and identify heavy metal pollutant contributions of various near-shore and offshore industries such as desalination plants and oil and gas exploration and extraction facilities in Abu Dhabi waters. Furthermore, information on heavy metals will aid in managing marine pollution by enlightening policymakers about heavy metal issues in an ecologically extreme environment.

2 Materials and methods

2.1 Description of the study area

The UAE is situated in the southern part of the Arabian Gulf, bordered on the west by Qatar and Saudi Arabia, on the south by the Sultanate of Oman and Saudi Arabia, on the north by the Arabian Gulf, and on the east by the Sultanate of Oman. The UAE comprises seven emirates that include Abu Dhabi, Dubai, Sharjah, Ajman, Umm Al Quwain, Ras Al Khaimah, and Fujairah. The coastline of Abu Dhabi Emirate, including that of Abu Dhabi Island, is 700-km long (Statistical Yearbook of Abu Dhabi, 2016^[50]). The mainland is bordered by many desert islands with fringing mangroves and surrounding shallows containing coral reefs and seagrass meadows. Abu Dhabi City is the largest one along the coast; smaller towns punctuate the coastline to both the east and west. Maintenance of marine water/sediment quality will protect both the public health and biodiversity of Abu Dhabi's coastal environments. Most of the Abu Dhabi landmass is a desert with scattered oases. These ecosystems are under ever-increasing pressure from anthropogenic activities associated with rapid economic, social, and industrial development in the Arabian Gulf, including Abu Dhabi. The climate of Abu Dhabi is hot; on the coast, humidity reaches over 90 percent in summer and autumn. The temperature is high, often exceeding 50°C in summer. During winter, daytime temperatures are generally in the mid-twenties Celsius; nights can be relatively cool, with temperatures as low as 12–15°C, dipping to 5°C in the depths of the desert or high in the mountains. In the marine environment, the surface water temperature oscillates between 17°C and 35°C, with an average salinity of 44 psu peaking at 70 psu in shallow areas.

The floor of the Arabian Gulf basin is asymmetric, sloping gently on the Arabian side and steeply on the Iranian flank. Abu Dhabi seabed features a sedimentary basin with a dominant benthic substratum in the coastal regions, constituting carbonate sediment formed from fragmented skeletons of benthic organisms. Most of the terrigenous particles transported to the sea surface are destined to become seafloor sediments, usually very fine-grained. Furthermore, skeletons of marine organisms are responsible for biogenic sediments, mostly very fine. With no fluvial input on the Arabian side, sediment accumulation is almost pure carbonate (Purser and Seibold, 1973^[47]). Aeolian terrigenous sediments carried by the Shamal wind are the reason for fine sand silt and clay with high carbonate (calcite and dolomite) content (Foda et al., 1985^[24]).

2.2 Sampling and analysis

Abu Dhabi's territorial waters were divided into many grids with 17-km intervals (Figure 1), and samples were collected at the center point of each. Each of the 117 grids was assigned a unique number to identify the sampling sites. The study was conducted in March 2015. Surface sediments were collected from each site using a sediment sampler (Peterson Grab), and sub-samples were taken

from the uppermost layer of the sediment to minimize contamination. After collection, all samples were stored in ice-packed coolers and transported to an external laboratory. They were refrigerated in the laboratory at 4°C to preserve their integrity and inactivate microbes, followed by testing for heavy metals, including Cu, Zn, Mn, Fe, Ni, Hg, Cd, Cr, Co, and Pb, employing the American Public Health Association (APHA) standard method 3120B (22nd edition).

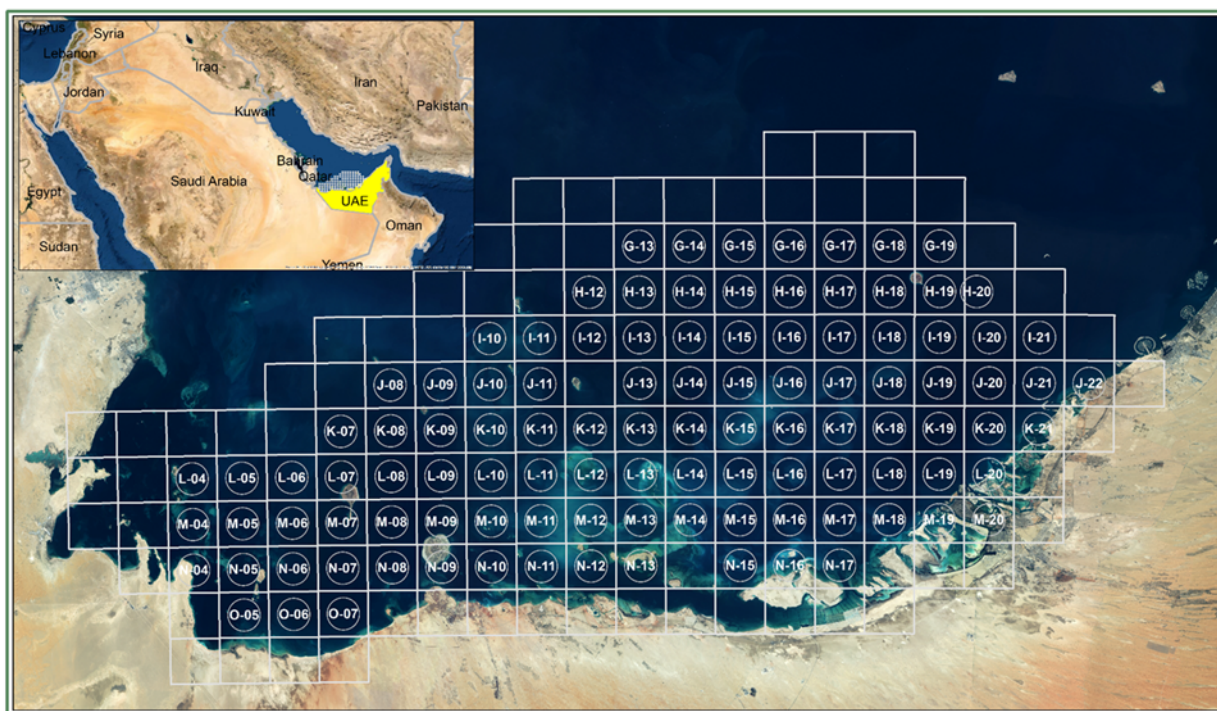


Figure 1. Sampling site – Map showing the location of the 106 sampling sites covers the Abu Dhabi territorial waters

2.3 Statistical analysis

Statistical methods were applied to assess the analytical data in terms of distribution and correlation among the studied parameters. Pearson's correlation coefficient analysis was performed to identify the relationship between the heavy metals in sediments and their possible sources. Principal component analysis (PCA) of the normalized variables was performed to extract significant principal components (PCs) and further reduce the contribution of variables with minor significance. The commercial statistics software package SYSTAT for Windows was used to perform statistical analyses in the present study. Agglomerative hierarchical clustering (AHC) analysis was conducted on the normalized data set using SPS software with Euclidean distances as a measure of similarity to assess the interrelationships between the sampling sites.

2.4 Geo-accumulation Index (I_{geo})

The geo-accumulation index introduced by Muller (1969^[40]) was used to assess the degree of metal pollution by comparing current concentrations with pre-industrial levels. It was calculated using the following equation (Muller, 1969^[40]):

$$I_{geo} = \log_2(C_n/1.5B_n)$$

where C_n is the measured concentration of the heavy metals in the sediments, B_n is the geochemical background value in average shale of element n and 1.5 is the background matrix correction due to terrigenous effects. The I_{geo} classification comprises seven classes (0–6), ranging from unpolluted to extremely polluted (Table 2).

2.5 The Enrichment Factor (EF) of heavy metals

The EF (Simex and Helz, 1981^[52]) was employed to assess the degree of contamination and understand the distribution of the elements of anthropogenic origin from the sites by individual elements in the sediments. Fe was chosen as the normalizing element when determining EF values, as in wetlands it is mainly supplied from sediments and is one of the widely used reference elements (Sheshan et al., 2010^[51]; Chakravarty and Patgiri, 2009^[18]; Loska et al., 2003^[37]). Other widely used reference metal elements are Al and Mn (Ong and Kamaruzzaman, 2009^[44]).

$$\text{Enrichment factor} = (\text{Cn/Fe})_{\text{sample}} / (\text{Cn/Fe})_{\text{background}}$$

where Cn is the concentration of the element "n." The background value is that of average shale (Muller, 1969^[40]). The EF classification constitutes six categories, from background concentration to extremely high enrichment (Table 2) (Sutherland, 2000^[55]).

2.6 Contamination Factor (CF)

The CF analysis is another important tool for assessing heavy metal pollution in the marine environment. For CF computation, values for metals such as Fe, Mn, Cd, Pb, Cu, Cr, and Zn are normalized using corresponding average metal values of shale (Turekian and Wedepohl, 1961^[59]). This is because world shale averages of these elements are considered to be the background values. CF was evaluated using the following equation:

$$CF = \text{Metal concentration in polluted sediment} / \text{Background value (shale) of the metal.}$$

The CF value classified the sediment into four categories from low to very high contamination (Table 2) (Hakanson, 1980^[28]).

2.7 Pollution Load Index (PLI)

The PLI was used to evaluate the extent of pollution by heavy metals in the environment. The range and classes are the same as for the Igeo. The PLI for a particular site was calculated following the method proposed by Tomlinson et al., (1980^[58]). The PLI for each sample was calculated as shown below:

$$\text{Pollution load index} = (C_{f1} \times C_{f2} \times \dots \times C_{fn})^{1/n}$$

where n is the number of metals and Cf is the contamination factor. A PLI value > 1 indicates pollution, whereas PLI value < 1 indicates no pollution (Sheshan et al., 2010^[51], Chakravarty and Patgiri, 2009^[18]). This empirical index provides a simple, comparative means for assessing the level of heavy metal pollution. The classification of PLI consists of 0 to 1 from perfection to progressive deterioration (Table 2) (Tomlinson et al., 1980^[58]).

2.8 Ecological Risk Index (ERI)

The ERI was used to evaluate the magnitude of pollution by heavy metals in the marine environment. The ERI for a particular site was calculated following the method developed by Hakanson (1980^[28]). The ERI for each sample was calculated as shown below:

$$ER^i = Tr^i \cdot C_f^i$$

$$C_f^i = C_o^i / C_n^i$$

The ERI is the potential ecological risk factor for a given element I , Tri is the toxic-response factor for the element i (e.g., $Cd = 30$, $Cu = Pb = Ni = 5$, $Cr = 2$, $Zn = 1$), Cf_i , Co_i , and Cn_i are the Cf , concentration in the sediment, and background reference level for element i , respectively. Potential ERI classification comprises five classes ranging from low to very high risk (Table 2).

3 Results and discussion

Heavy metals are a natural component of the earth's crust; hence, natural processes such as weathering and erosion cause metals to be washed away from the land and transported to the oceans. However, increased industrial activity means that human activity is now the largest contributor to heavy metal concentration in ocean waters. The majority of metals dissolved in the ocean waters come from the atmosphere, with an increase in atmospheric concentrations over the past few hundred years, leading to an increase in ocean metal concentrations. The concentration of metals in seawater is usually insufficient to kill immediately, but it weakens animals and reduces their biological activity, increasing stress on marine populations. Compounded by additional stressors such as climate change, metal contamination can lead to an irrecoverable population drop, changing the balance of the ocean's ecosystem.

Localized increases in metal concentration in coastal waters are the most likely changes to have a direct impact on humans. Japan's Minamoto Bay incident is the best example of the impacts of heavy metals on the marine environment and human health. Heavy metals normally occur at very low levels in the environment. They exert a variable range of toxicity and effect; while some such as Mn, Fe, Cu, and Zn are essential metal micronutrients, others such as Hg, Cd, and Pb are not required even in small amounts by any organism (Fergusson, 1990^[23]; Luoma, 2000^[38]). The latter metals are stable and exist as persistent environmental contaminants that can severely affect organisms and the environment. They are known as heavy metals, which are very toxic and tend to accumulate in the soils and sediments (Williamson et al., 2003^[61]). Over time, they accumulate within the sediment that becomes an important reservoir of the metal concentrations, providing a record of pollution loading in marine ecosystems.

3.1 Cadmium

Cadmium is highly toxic, bio-accumulative, and carcinogenic to human beings. Apart from natural earth crust diffusion, anthropogenic activities are the major source of cadmium in the coastal marine environment. Concentrations of cadmium in the sediment collected in Abu Dhabi territorial waters ranged from 0 to 0.66 mg/kg. The maximum concentration was recorded in grid number G-16 (0.66 mg/kg) and low values were observed in H-13 (Figure 2). Comparing mean values observed in the present study (0.145 mg/kg) with the observations made in other Arabian Gulf countries, including Abu Dhabi waters, revealed higher values such as in the study by De Mora et al., (2004^[19]) in Abu Dhabi (0.02 µg/g), Mirfa (0.11 µg/g), Al Ruwais (0.11 µg/g), Umm Al Quwain (0.21 µg/g), Jebal Ali (0.05 µg/g), Qatar (0.09 µg/g), Bahrain (0.19 µg/g), Saudi Arabia (0.14), and Oman (0.18 µg/g). However, values observed in the present study were lower than the findings made in other countries such as in Yemen by Al Adrise (2002^[03]) (14.2 µg/g), Saudi Arabia by Al Najjar et al., (2011^[08]) (5.25 µg/g), and the Indian east coast by Solai et al., (2013^[53]) (2.76 µg/g).

3.2 Chromium

Chromium is one of the least toxic elements based on its oversupply and essentiality. Generally, the mammalian body can tolerate 100–200 times its total body content of Cr without harmful effects (Prosi and VanLierde, 1979^[46]). It is widely used in household and engineering products.

The concentration of chromium detected in the sediment samples collected in Abu Dhabi territorial waters ranged from 0.41 to 19.36 mg/kg, with an average of 5.06 mg/kg. Maximum concentrations were recorded in grid N-09 (19.36) and low values were observed in N-15 (Figure 2). Chromium concentrations in marine sediments reported by others in the UAE and other countries showed that the concentration observed presently in Abu Dhabi waters was lower than the previous observations. De Mora et al., (2004^[19]) reported in Abu Dhabi (17.6 µg/g), Al Mirfa (37.6 µg/g), Al Ruwais (171 µg/g), Umm Al Quwain (71.9 µg/g), Jebal Ali (31.7 µg/g), Qatar (40.8 µg/g), Bahrain (9.86 µg/g), Muscat (357 µg/g), Kuwait (140 µg/g), and Saudi Arabia (32 µg/g). Furthermore, Kumar and Ramanathan (2013^[34]) recorded 163 mg/kg on the west coast of India. However, the values (1.12 µg/g) observed in the Red Sea Gulf of Aqaba (Al Najjar et al., 2011^[08]) were lower than the present observation.

Table 1. Maximum, minimum and mean values of different heavy metals distributed in Abu Dhabi waters

Heavy Metals	Cadmium (mg/kg)	Chromium (mg/kg)	Cobalt (mg/kg)	Copper (mg/kg)	Iron (mg/kg)	Manganese (mg/kg)	Nickel (mg/kg)	Lead (mg/kg)	Zinc (mg/kg)	Mercury (mg/kg)
N of cases	106	106	106	106	106	106	106	106	106	106
Minimum	0	0.41	0	0.89	163	0	0	0	0.65	0
Maximum	0.66	19.36	2.46	8.47	6372	147.1	18.1	11.86	35.41	0
Range	0.66	18.95	2.46	7.58	6209	147.1	18.1	11.86	34.76	0
Mean	0.145	5.056	0.359	2.761	1275.121	29.775	2.795	0.489	4.883	0
Standard Dev	0.117	3.313	0.515	1.297	1033.429	24.206	3.763	1.27	4.336	0

3.3 Cobalt

The concentration of Co ranged from 0 to 2.46 mg/kg in sediment samples collected from Abu Dhabi waters. The highest value of Co (2.46 mg/kg) was recorded in grid M-06, followed by N-09 and N-05. The minimum values (0 mg/kg) were recorded in more than 30 sites (Figure 2). The mean values detected were 0.359 mg/kg. The observations made by others proved that concentrations currently observed in Abu Dhabi waters were lower than many other Arabian Gulf countries and international waters (Table 6), except the observation made by De Mora et al., (2004^[19]) at Abu Dhabi (0.34 µg/g), which was comparable with the present findings. No highly elevated concentrations of Co were observed, although it is enriched above natural values. Notably, the choice of reference value for normalization alters the degree of enrichment.

3.4 Copper

Copper is a micronutrient for aquatic life but becomes toxic at higher levels. Contamination in natural sediments is often related to anthropogenic activities. Moreover, copper is often associated with sewage sludge, likely in organo-metal complexes with a variety of organic compounds. The concentration of copper in the sediments collected in Abu Dhabi waters varied from 0.89 to 8.47 mg/kg (Figure 2). The maximum concentration of 8.47 mg/kg was found in grid N-09, followed by N-05 and M-06. The minimum value was 0.89 mg/kg, noted at M-17, and the average value detected was 2.761 mg/kg. Comparing mean values observed in the present study (2.761 mg/kg) with other observations made by De Mora et al., (2004^[19]) in the Arabian Gulf countries showed higher values in Al Mirfa (3.58 µg/g), Umm Al Quwain (5.03 µg/g), Qatar (8.17 µg/g), Saudi Arabia (3.24 µg/g), and Oman (10 and 04 µg/g). Al Shemmari et al., (2010^[06]) recorded higher values than the present study in Kuwait (36.7 mg/kg). Kumar and Ramanathan (2013^[34]) observed higher values on the west coast of India (84 mg/kg). Amin et al., (2009^[12]) recorded higher values than Abu Dhabi in the Indonesian

waters (46.3 mg/kg). Furthermore, higher values were documented in Korean waters by Kim et al., (2010^[31]) (5.83 µg/g), in Bremen Bay in Germany by Pekey (2006^[45]) (87 mg/kg), and in Malaysia by Wei Hssiang et al., (2016^[60]) (6.49 mg/kg) (Table). The high concentrations observed in coastal transects can be attributed to industrial effluents, industrial water coolant discharge, combustion of coal in power plants, municipal domestic sewage, and harbor operations.

3.5 Iron

In the study area, Fe values ranged from 163 to 6372 mg/kg, and the average value was 6209 mg/kg (Table 1). Fe concentrations in Abu Dhabi marine sediments showed higher concentrations than other metals. The highest value of Fe concentration was found in grid N-09 (6372 mg/kg), followed by N-05 and M-06 (4238 and 4223 mg/Kg, respectively). The lowest values were observed in K-12 (163 mg/kg) and N-15 (181 mg/kg). The mean value was 6,209 mg/kg. Iron concentrations observed in the present study were lower than observations made by De Mora et al., (2004^[19]) in Muscat and the Salalah of Sultanate of Oman (2,2749 µg/g and 11,369 µg/g, respectively). However, they are comparable with values observed in the UAE such as Al Mirfa (5,820 µg/g), Al Ruwais (8940 µg/g), and Umm Al Quwain (6,055 µg/g) (De Mora et al., 2004^[19]). Jebal Ali in the UAE exhibited lower values (2,740 µg/g) than other places in the UAE (De Mora et al., 2004^[19]). A very high concentration (733114 mg/kg) of iron was recorded on the west coast of India (Kumar and Ramanathan, 2013^[34]).

3.6 Manganese

Manganese exists as Mn oxides in industrial sources and weathering products. It is an essential nutrient for most plants. In the study areas, manganese values ranged from 0 to 5,147.1 mg/kg and the average value was 29.78 mg/kg. The highest value was detected in grid N-9, followed by M-06 and K-07. The lowest value was observed in L-09 (0 mg/kg) (Table 1). Manganese concentration detected in the present investigation was lower than the observations of De Mora et al., (2004^[19]) in Al Mirfa (225 µg/g), Al Ruwais (231 µg/g), and Umm Al Quwain (96.6 µg/g). Moreover, Qatar, particularly, Umm Said (84.9 µg/g), and Muscat in Oman (3100 µg/g) showed higher values than the present observation. Moreover, Saudi Arabia and the Red sea showed higher values than Abu Dhabi Emirate (Table 6). India recorded 1025 mg/kg on the west coast and 235.4 mg/kg on the east coast (Kumar and Ramanathan, 2013^[34]).

3.7 Nickel

Nickel is a nutritionally essential trace metal for several animal species, microorganisms, and plants. In general, nickel concentration was low in many places; however, we found very high concentration in few places, particularly in grid L-09 (18.01 mg/kg), followed by M.06 (16.05 mg/kg), N-05 (15.08 mg/kg), M-20 (13.56 mg/kg), etc. The mean value recorded in Abu Dhabi waters was 2.79-mg/kg lower than the values observed in other places of the UAE, Qatar, Bahrain, Kuwait, Oman, Saudi Arabia, and India (Table 6). Even though the values of Ni in the present study are low and indicate lithogenic origins, they are still sufficiently high to suggest an anthropogenic contribution.

3.8 Lead

Lead is a heavy metal that occurs in nature mainly as lead sulfide. Its major source in Abu Dhabi is anthropogenic, including oil and gas exploration and extraction. Moreover, lead has been used in a variety of paints and is a common constituent of municipal and industrial wastes. The concentration of Pb ranged from 0 to 11.86 mg/kg in Abu Dhabi waters. The highest concentration of Pb (11.86 mg/kg) was detected in grid J-15 and the minimum value of 0 mg/kg was recorded in 65 sites (Figure 2). The mean value calculated was 0.489 mg/kg. Lead concentration recorded in the present study was

lower than the observations made in Al Mirfa (2.93 µg/g), Al Ruwais (5.88 µg/g), Umm Al Quwain (2.54 µg/g), Jebal Ali (2.1 µg/g), Umm Said in Qatar (3 µg/g), Bahrain (11 µg/g), Muscat (6.9 µg/g), Kuwait (10.5 µg/g), and Saudi Arabia (1.7 µg/g) by De Mora et al., (2004^[19]). Furthermore, the value (4.07 µg/g) observed in the Gulf of Aqaba in the Red Sea (Al Najjar et al., 2011^[08]) was higher than the present observation. Kumar and Ramanathan (2013^[34]) recorded 20 mg/kg on the west coast of India.

3.9 Zinc

Zinc is an essential trace metal present in mafic minerals. It is an important component of the plant and the human body. Besides its nutritive effect, zinc is toxic to most forms of plants when present in amounts exceeding certain limits. In the marine environment, the distribution of Zn concentration is expected to be controlled by variations in the grain size of the sediments. In the study area, zinc values ranged from 0.65 to 35.41 mg/kg and the average value was 4.88 mg/kg (Table 1). The samples collected from grid J-15 showed the highest value (35.41 mg/Kg) and the minimum value (0.65 mg/Kg) was detected in grid L-09.

Zinc concentrations found in the present study were higher than observations made by Fowler et al., (1985^[25]) in Umm Al Quwain (3.4 µg/g), Bahrain (2.34 µg/g), and Saudi Arabia (2.34 µg/g). Higher concentrations were detected by De Mora et al., (2004^[19]) in Muscat and Salalah (26.3 and 24.5 µg/g, respectively), Al Shemmari et al., (2010^[06]) in Kuwait (93.3 mg/kg), Kumar and Ramanathan (2013^[34]) on the west and east coasts of India (107 mg/kg and 52.04 mg/kg respectively), and Pekey (2006^[41]) in Breman Bay, Germany (790 mg/kg) (Table 6).

Among the 10 heavy metals analyzed in the sediments collected from the 106 sites, iron concentrations were higher than other metals, followed by manganese; cobalt showed the lowest concentrations, with mercury concentrations consistently below the detection limit in all the sampling sites. In general, the concentration order recorded was **Fe > Mn > Cr > Zn > Ni > Cu > Pb > Co > Cd > Hg**.

3.10 Spatial variation of heavy metal concentrations

Information on the spatial distribution of different heavy metals is essential to elucidate the dispersion of the contaminant within a particular geographical location. It provides a visualization of the spatial pattern and enormity of the pollution through the generation of a contour map via a Geographic Information System (GIS). The objectives of spatial analysis are to measure properties and identify relationships and differences, taking into account spatial localization. The present investigation incorporated spatial analysis of various transects examined within Abu Dhabi waters. The application revealed notable differences between metals in the study area.

Every metal, except lead and zinc, which appeared to behave distinctly, showed elevated concentrations near Baraka and Sir Bani Yas area and lower concentrations near the central region. Though high concentrations of cadmium were recorded near Baraka, the highest values were recorded near the northeast border. Moreover, cadmium, cobalt, and iron exhibited higher concentrations near the northeast border. The distribution of nickel was slightly different from other metals, with elevated concentrations not only observed near Baraka and the northeast border but also in Abu Dhabi's island coastal waters, except the central offshore areas where the concentrations were low. The distributions of lead and zinc were somewhat different from other metals. Higher concentrations were noted near the central offshore oil and exploration and operation areas and the Baraka area. Lower concentrations were recorded in the eastern waters of Abu Dhabi up to the Dubai border.

Several noteworthy observations can be made regarding the distribution of heavy metals in marine sediments of Abu Dhabi waters. Concentrations of metals, except lead and zinc, were lower in coastal areas, where the anthropogenic activity is greater while they were elevated in various pockets, particularly in the Western Region (Baraka area) and the northeast border of Abu Dhabi's territorial waters. The present study reveals that the distribution of heavy metals in the sediments of Abu Dhabi waters is not only determined by metal enrichment but also by other complex factors such as the current patterns, sediment characteristics, topography, and water depth. Luoma (2000^[38]) pointed out that metal enrichment in sediments was usually located close to past and present sources of pollution. Concentrations drop with distance from the source, as determined by the physical processes that dilute and redistribute particles with which metals associate, as in the case of dilution with less contaminated sediments (Fergusson, 1990^[23]; Luoma, 2000^[38]). However, the rate of decline in concentration with distance from the sources of pollution is extremely variable (Williamson and Wilcock, 1994^[62]). In Abu Dhabi waters, mostly higher concentrations were recorded away from the coast.

The distribution of high concentrations of metals in the Western Region, particularly the Baraka area could stem from nearby sources such as oil exploration, refinery activities, fertilizer production, and oil export-related activities at Ruwais port. Furthermore, the Western Region receives waters from neighboring countries through the anti-clockwise circulation of the Arabian Gulf waters (Alosairi and Pokavanich, 2017^[9]). Developmental activities carried out in the coastal areas of nearby countries adversely affect Abu Dhabi waters. When the pollutants transported by water currents reach Abu Dhabi waters, bottom topography (depth) and sediment (muddy clay) play major roles in their accumulation and retention, particularly in the Western Region near Baraka and Sir Bani Yas Island. Here topography is significant; both the Baraka and Abu Al Abyadh areas feature relatively deep, and water movement in those areas was very slow, resulting in greater residential times for the water, thus providing an opportunity for settling and increased binding of metals with the sediments.

The highest accumulations in the northeastern area could be due to the water current patterns, mainly the bottom current, with high density/high saline seawater at the bottom moving toward the Straits of Hormuz—the current that plays a major role in the movement of pollutants, particularly heavy metals. Sediments with pollutants from the coastal areas are carried offshore. The depth and nature of the sediments play a major role in the accumulation of pollutants, particularly heavy metals. When comparing the distribution pattern of various metals, lead and zinc behave entirely differently from other metals, mainly accumulating in the central oil exploration and operation areas. This was borne out by the PCA (Figure 4) and factor analysis.

The sediment nature/texture plays a huge role in heavy metal accumulation in surface sediments. Luoma (2000^[38]) reported that metal concentrations in marine sediments are determined not only by metal inputs but also by sediment characteristics. Grain size distribution is recognized to affect trace metal concentrations in estuarine and marine sediments. Krumgalz et al., (1992^[33]) specified that the enrichment of the silt/clay fraction by anthropogenic trace metals is due to the large specific area of this fraction and strong adsorptive properties of clay minerals. Loomb (2001^[36]) stated that fine-grained sediment of this particular fraction has a high absorption potential given its large surface area to volume ratio and large amounts of interstitial water. Fergusson (1990^[23]) detailed that the feature of fine-grained sediment, significant for trace metals, is its ability to absorb metal ions by their outer sheath of hydroxyl groups. Moreover, fine-grained minerals have a higher surface area to volume ratio and can absorb material into their lattice framework (Loomb, 2001^[36]).

Sediments collected from Abu Dhabi waters were classified into three categories: muddy clay, medium/coarse sand with gravel, and hard bottom with shells and gravels. Among the 106 sampling sites, 52 percent had medium sand with gravels, 29.55 percent had muddy clay, and 19.2 percent had a hard bottom with shells. The concentration of heavy metals was higher in muddy clay sediments. This was in agreement with the findings of Nasser (2013; 2012^[42&43]). He found that sediment samples collected from the near-shore area between Kuwait and Qatar exhibited a trend of increasing particle size from the north to the south of the Arabian Gulf. Metal levels were high in the mud samples collected off the Kuwaiti coast and decreased to the south, as sand fraction increased.

According to the PLI, high values (0.12–0.17) were recorded in places where the muddy clay nature of sediments was available (Figure 3), specifically in grids N-09, N-05, N-06, G-16, M-06, K-16, J-15, J-19, etc. After them, higher metal values were observed in medium/coarse sand with gravel, particularly in grids G-19, H-12, J-22, K-15, etc. The lowest PLI values (0) were detected in areas with hard bottom and shells such as G-13, H-20, I-17, N-15.

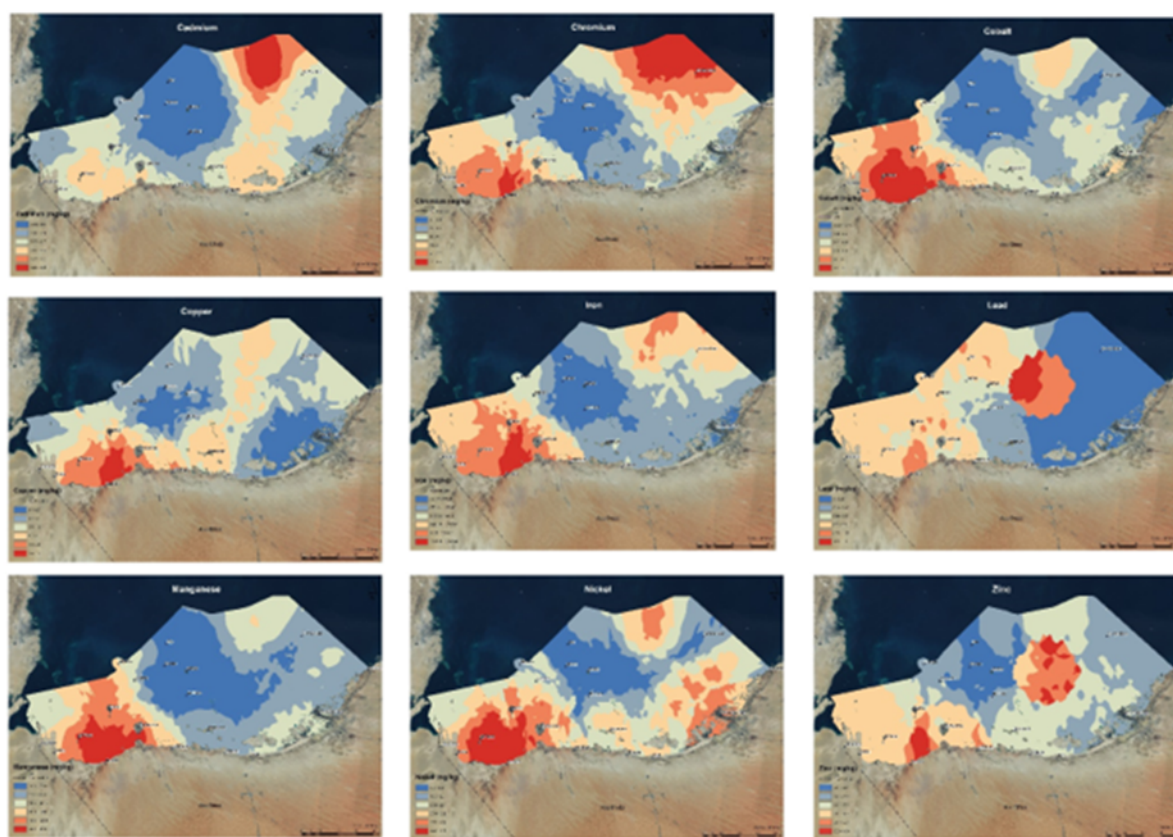


Figure. 2. Spatial distribution of heavy metals in sediments collected from Abu Dhabi territorial waters.

Besides the nature of the bottom/sediment, water depth affects heavy metal concentrations in surface sediments. The present investigation showed that high PLI values were recorded in areas with high depths such as grid G-16 with 25 m, N-9 with 14m, N-05 with 24 m, M-06 with 27 m, K-18 with 25 m, I-20 with 25 m, K-08 with 35 m, etc. Shallower areas had low PLI values (Figure 3). Results observed indicate that depth alone does not play a major role in accumulating and concentrating heavy metals but that the texture of the sediment also influences metals concentrations. In Abu Dhabi waters, various statistical analyses and several index calculations revealed that most metal concentrations in surface sediments were below international standards (Table 5).

3.11 Relationship between metals

Correlation analyses effectively elucidated relationships between multiple variables, enabling to understand the factors and sources that govern chemical components. Heavy metals in the environment normally exhibit complex relationships. Significantly high correlations between heavy metals may indicate that their accumulation derives from similar pollution sources (Alba et al., 2011^[07]; Manta et al., 2002^[39]). In the present study, concentrations of Mn, Co, and Fe exhibited highly positive relationships (Table 4). The relationships between Fe, Cr, and Co were moderately positive. Pb showed much less of a relationship with other metals; however, it was slightly positive. Zn showed a significantly positive relationship with Cd, Cr, Co, Cu, Fe, Mn, and Pb, whereas Ni showed a very weak relationship with Zn.

3.12 Assessment of heavy metal pollution

3.12.1 Enrichment Factor (EF)

The EF is an effective method for distinguishing between natural and anthropogenic sources of pollution and has been widely used for over 30 years (Li et al., 2012^[35]; Zhang and Liu, 2002^[64]). To eliminate the influence of grain size and mineral composition on elemental concentrations and identify possibly anomalous metal concentrations, heavy metal concentrations are generally normalized by conservative elements such as Al, Fe, and Sc (Herut et al., 1993^[30]; Grousset et al., 1995^[27]; Aloupi and Angelidis, 2001^[10]; Amin et al., 2009^[12]). In this study, we selected iron as a conservative tracer to differentiate between natural and anthropogenic components. According to EF values, each sample falls into one of the six categories (Table 2) (Sutherland, 2000^[55]). The ranges and mean values of the EFs calculated for each metal in the sediments are shown in Table 3. The analysis indicated that a few metals such as Cd, Ni, Pb, and Zn showed significant enrichment in one or two sites only and that more than 95 percent of the sites were clear with no enrichment of heavy metals (and maybe no anthropogenic enrichment).

Table 2. Enrichment Factor, Geo –accumulation Index, Contamination Factor, Pollution Factor classification details

Enrichment Factor (EF)		Geo-accumulation index (I _{geo})		Contamination Factor (Cf)		Pollution Load Index (P _{LI})		Potential Ecological Risk Factor (ER)	
EF Value	EF Classification	I _{geo} Value	I _{geo} Classification	Cf Value	Cf Classification	PLI Value	PLI Classification	ER Value	ER Classification
< 1	No enrichment	≤ 0	Uncontaminated	Cf < 1	Refers to low contamination,	< 1	Indicates no pollution	≤ 40	Low risk
1 - 3	Minor enrichment	0 - 1	Uncontaminated to moderately contaminated	≤ Cf < 3	≤ Cf < 3 means moderate contamination	> 1	Indicates pollution	40 < ER ≤ 80	Moderate risk
3 - 5	Moderate enrichment	1 - 2	Moderately contaminated	≤ Cf < 6	Indicates considerate contamination			80 < ER ≤ 160	Considerable risk
5 - 10	Moderately severe enrichment	2 - 3	Moderately to heavily contaminated,	Cf > 6	Indicates very high contamination			160 < ER ≤ 320	High risk
10 - 25	Severe enrichment	3 - 4	Heavily contaminated					320 < ER	Very high risk
25 - 50	Very severe enrichment	4 - 5	Heavily to extremely contaminated						
> 50	Extremely severe enrichment	5 - 6	Extremely contaminated						

3.12.2 Geo-accumulation Index

According to the Müller scale (Müller, 1981^[41]) (Table 2), the mean geo-accumulation indices of all metals suggest that the Abu Dhabi marine sediment was not polluted overall by these metals. However, the mean geo-accumulation indexes of Cd reached 0.55, indicating higher cadmium levels than the other metals in the sediment collected from Abu Dhabi waters.

3.12.3 Contamination Factor (CF)

The CF was calculated for every metal analyzed in the 106 sites. According to the classification of pollution level indices (Table 2), cadmium showed highest CF value (2.2), which indicates that moderate contamination occurred in grids G-16, H-16, H-17, K-16, M-06, N-05, N-09 and N-16., and that only 7.5 percent of the sites showed moderate contamination.

3.12.4 Pollution Load Index (PLI)

The PLI was calculated based on the plan followed by Tomlinson et al., (1980^[58]). It did not show much fluctuation (Table 2). The PLI values observed were < 1 for all metals, which means all samples were free of metal contamination to some extent. Lower values of PLI imply no appreciable input from anthropogenic sources. Hence, metal pollution is not present in the sampling sites.

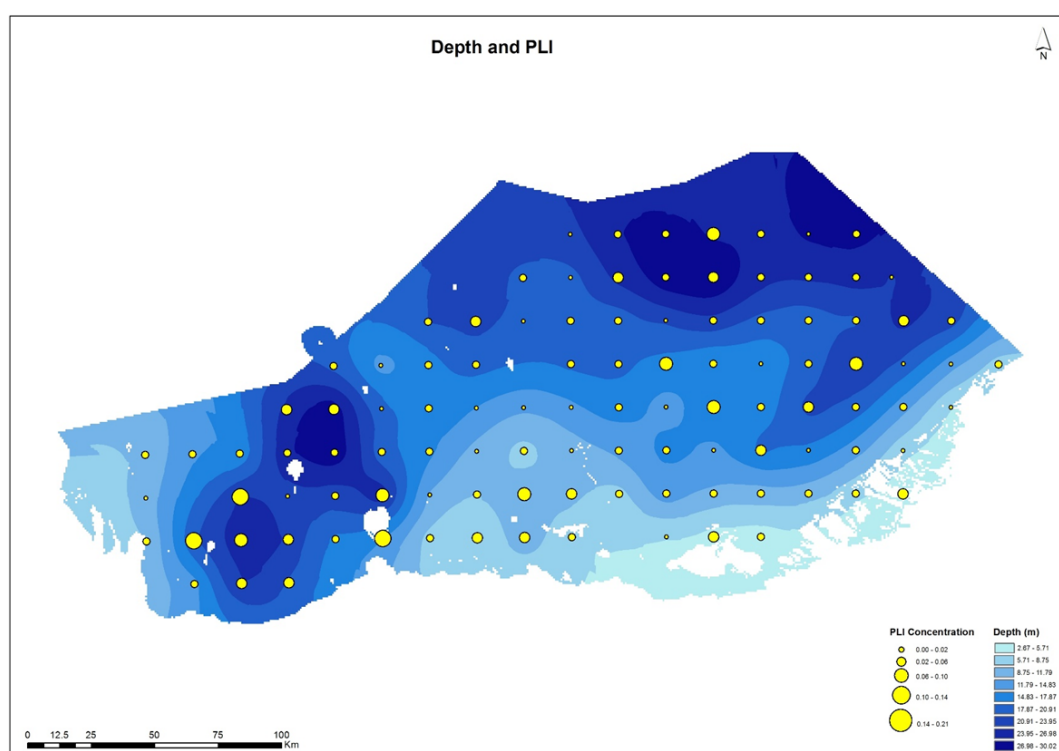


Figure 3. Relation between the depth and pollution Load index (PLI) in Abu Dhabi territorial waters.

3.12.5 Ecological Risk Index (ERI)

The ERI showed that Cd had the highest potential risk. The EF and Igeo indices are calculated mainly based on the concentrations of the total metals and enrichment levels. The ER index is based on the toxic response factor besides the total concentration. For example, although the total concentration of Cd is usually pretty lower than Zn in sediments, the higher value of the toxic-response factor of Cd ($Tr = 30$) might make it much more toxic than Zn whose toxic response factor is only 1. In the present investigation, the ER index revealed that among all the metals studied, only cadmium showed moderate risk, particularly in grids G-16, H-16, H-17, and K-16, and that the grids were located in the circle of Al Dhafra petroleum operations. However, other areas did not show any kind of risk in Abu Dhabi waters.

Table 3. Enrichment Factor, Geo –accumulation Index, Contamination Factor, Ecological Risk Index

Heavy Metals	Enrichment Factor			Geo-accumulation Index			Contamination factor			Ecological Risk Index		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Cadmium (mg/kg)	0	92.82	20.69	-5.64	0.55	-1.99	0.00	2.20	0.48	0	66	14.55
Chromium (mg/kg)	0.98	5.56	2.43	-6.64	0	-4.96	0.00	0.22	0.06	0.01	0.43	0.11
Cobalt (mg/kg)	0	2.33	0.49	-6.64	0	-3.18	0.00	0.13	0.02	0.1	0.94	0.31
Copper (mg/kg)	0.97	14.55	3.29	-6.64	-2.94	-4.76	0.02	0.19	0.06			
Iron (mg/Kg)				-6.64	0	-5.23	0.00	0.14	0.03			
Manganese (mg/kg)	0	4.7	1.42	-6.64	0	-5.39	0.00	0.17	0.04			
Nickel (mg/kg)	0	23.15	1.34	-6.64	0	-3.61	0.00	0.27	0.04	0	1.33	0.21
Lead (mg/kg)	0	18.77	1.02	-6.64	0	-1.89	0.00	0.59	0.02	0	2.97	0.12
Zinc (mg/kg)	0.6	10.33	2.46	-6.64	0	-5.07	0.01	0.37	0.05	0.01	0.37	0.05

Table 4. Pearson Correlation Matrix

	CD	CR	CO	CU	FE	MN	NI	PB	ZN	HG
CD	1									
CR	0.766	1								
CO	0.704	0.822	1							
CU	0.614	0.786	0.816	1						
FE	0.761	0.91	0.897	0.812	1					
MN	0.659	0.78	0.922	0.767	0.909	1				
NI	0.583	0.699	0.791	0.692	0.687	0.647	1			
PB	0.16	0.212	0.3	0.302	0.391	0.354	0.098	1		
ZN	0.552	0.616	0.688	0.683	0.739	0.667	0.483	0.781	1	
HG										1

3.12.6 Principal component analysis/factor analysis

The PCA is based on identifying variables most strongly correlated with each component. It was performed to identify interrelationships of the heavy metals distributed in the sediment samples collected from 106 different sites. The figure 4 showed there were two PCs for surface sediments in Abu Dhabi waters with eigenvalues larger than 1, and altogether, they accounted for 84.2 percent of the variance in the data of the Abu Dhabi waters.

The first PCA is strongly correlated with eight metals. This indicates that metals with values above 0.5 increase along with other metals. This suggests Cr, Co, Fe, Mn, Cu, Zn, Cd, and Ni vary together, i.e., if one increases, the others tend to as well. Furthermore, the first PCA correlates most strongly with Fe, Co, Mn, and Cr, with weak correlations with Zn, Cd, and Ni. However, Pb is very weakly correlated with other metals. This explains 70.1 percent of the total variance being positively related to Cr, Co, Fe, Mn, Cu, and Ni, indicating similar sources such as terrestrial and biogenic. Zn and Pb were only negatively related to PC2, indicating different sources for them than the other studied metals. Zn and Pb might be from anthropogenic and biogenic sources. Furthermore, previous studies have shown that a large amount of Pb is supplied by the precipitation of aerosols in coastal environments (Fytianos and Lourantou, 2004^[26]). Thus, the precipitation of aerosols might be another important source of Pb in the surface sediments of Abu Dhabi waters (Figure 4).

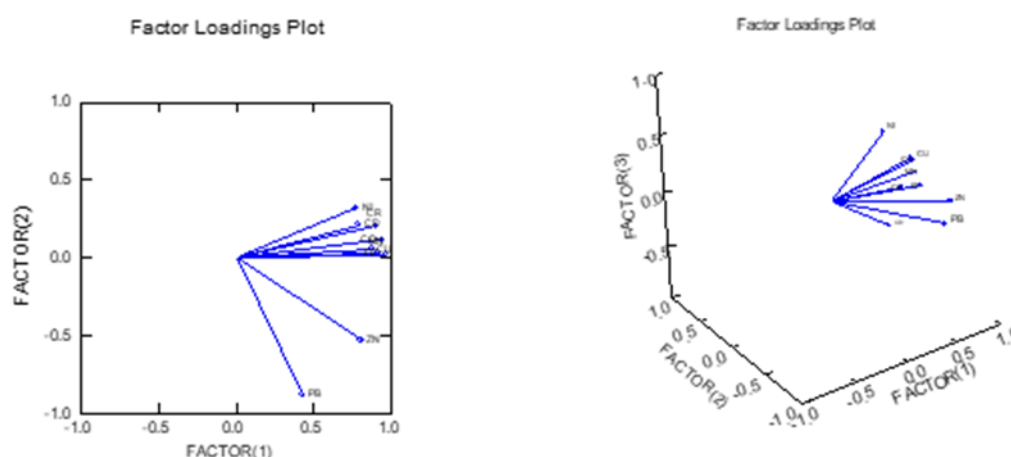


Figure 4: PCA Analysis- Factor values

3.13 Cluster analysis

Agglomerative hierarchical clustering (AHC) analysis includes contaminant metal (Cd, Cr, Co, Cu, Fe, Mn, Ni, Pb, Zn, and Hg) concentrations and separates the samples of studied transects into four main clusters according to the nature of the sediment and increasing heavy concentrations (Figure 5). The first cluster includes 74 (69.81 percent) of the total sites, showing the lowest values of PLI; the nature of the sediment in most of the sites was sandy. Sampling sites were mostly offshore and concentrations were less compared to those in sites covered in other clusters. Cluster 2 includes 20 (18.86 percent) of the total sites, representing the higher values of PLI than the site covered in cluster 1, with the nature of the sediment being sand with mud. Sampling sites were distributed throughout the territorial waters, except the central region. Cluster 3 includes 9 sites (8.49 percent of the total samples) and is characterized by moderate to high values of PLI, with the nature of the sediment distributed in that area characterized as muddy with higher concentrations of metals than sites covered in other two clusters. Cluster 4 comprises three sites (2.83 percent of the total samples). It has the highest values of pollution index and the highest concentration of heavy metals compared to sites covered in other clusters. The nature of the sediment was black muddy clay. The elevated levels of these metals reflect the influence of landfilling and dredging operations, besides terrestrial input in these areas (see the depth of these sites).

3.14 Source of heavy metals in Abu Dhabi waters

Heavy metals normally occur at very low levels in the environment. They exert a variable range of toxicity and effect; while some such as Mn, Fe, Cu, and Zn are essential metal micronutrients, others such as Hg, Cd, and Pb are not required even in small amounts by any organism (Fergusson, 1990^[23]; Luoma, 2000^[38]). They are stable and exist as persistent environmental contaminants, which impose havoc on the organisms and the environment. They are toxic and tend to accumulate in soils and sediments (Williamson et al., 2003^[61]). Over time, they accumulate within the sediments and the latter become an important reservoir of metal concentrations. The Arabian Gulf is considered to be among the highest anthropogenically impacted regions in the world (Halpern et al., 2008^[29]). The coasts of the Arabian Gulf, including Abu Dhabi, are witnessing rapid industrialization and urbanization that contribute to the degradation of marine ecosystems that are already naturally stressed. Major Major anthropogenic sources of heavy metals in the Abu Dhabi marine environment include reclamation and

dredging, sewage discharges, power generation and desalination, oil exploration, petroleum processing, shipping-related activities and industrial effluents, including iron and steel production, electroplating and galvanizing, chemical industries, textile and leather industries, glass manufacturing, pulp and paper production, etc.

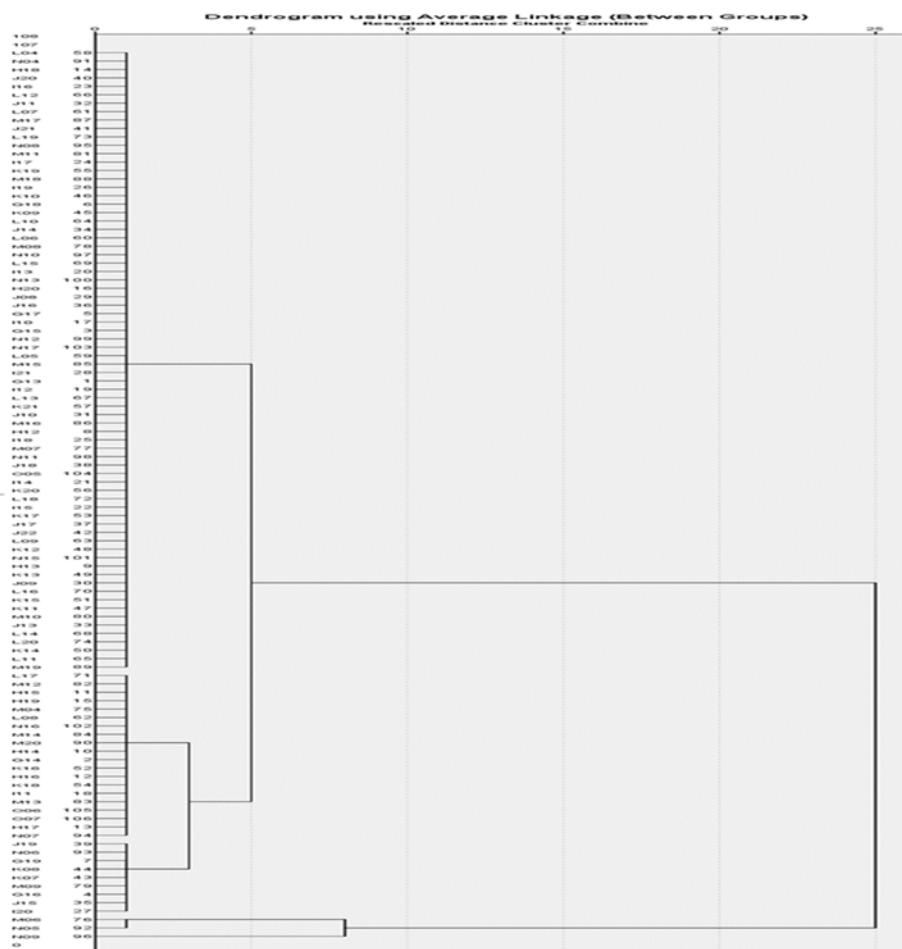


Figure 5. Dendrogram showing cluster of variables based on similarity

3.15 Management of heavy metal pollution

Coastal pollution is a severe problem in the Arabian Gulf countries due to the desalination plant discharges, man-made island construction, industrial and household waste dumped directly into the sea, and oil spills. Regulations related to heavy metal pollution have been developed in most countries of the Arabian Gulf, including the UAE. The Regional Organization for Protecting Marine Environment (ROPME, 2005^[49]) has developed environmental quality standards for selected heavy metals in wastewater effluents; they have been adopted in all the Arabian Gulf countries, including the UAE. Furthermore, Kuwait conventions that provide the basis for integrated regional response to fight pollution were adopted in 1978. Internationally, the UAE is a member of several international environmental agreements concerned with the protection of marine environments from pollution. Similarly, in the UAE, sophisticated environmental legislation has been promulgated, including several separate laws. Some apply at a federal level, others only at individual emirate level. The task of putting into practice what is enshrined in such laws backed up by monitoring and strict enforcement is now being addressed.

The UAE governments have been passing several significant laws and regulations to protect the marine environment. At the federal level, there is an environmental statute of general application, “Law No. 24 of 1999 regarding Protection and Development of the Environment.” This law covers every aspect of environmental protection including land, water, and air. It requires all governmental bodies concerned with planning, construction, and economic development to consider environmental protection, prevention of pollution, and the rational use of natural resources in carrying out their functions. Nationally, there are several laws concerning protecting the environment and combating environmental pollution that facilitate the implementation of related regional and international regulations and agreements.

The UAE Federal Law No. 24 of 1999 is the major comprehensive statute on environmental protection that serves as the starting point for understanding the environmental legal framework within the country. Within Abu Dhabi Emirate, Law No. 16 of 2005 specifies all of the Environment Agency – Abu Dhabi’s (EAD) responsibilities concerning the protection of the environment and public health. As such, the EAD initiated a monitoring program in 2006 that continues to date and collects data on marine water quality and sediment from 22 sites. Furthermore, the EAD automated marine water quality monitoring; the network expanded to more than 25 sites (EAD 10 buoys and Abu Dhabi Municipality 15 buoys) and served as a warning system for marine water quality and Harmful Algal Blooms (red tides).

To assess the status and trend of pollutants in the marine environment, the EAD developed three indices during 2012, relevant to the Emirate of Abu Dhabi: (1) *Eutrophication Index*, which tracks issues concerning increased nutrients from population and growth-related contamination, (2) *Microbial Index*, which tracks contaminants concerning the protection of public health during recreational water use, and (3) *Heavy Metals Index*, which tracks contaminants in marine sediments and is indicative of longer-term contamination trends. The indices calculated for Abu Dhabi were based on a method originally developed by the Canadian Council of Ministers of the Environment (CCME, 2001^[17]).

The EAD Heavy Metals Index was designed to indicate the level of contamination in sediments based on concentrations of six heavy metals: cadmium, copper, nickel, lead, zinc, and mercury. They were chosen because they are potentially more toxic than other metals (e.g., manganese, iron) (ATSDR, 2016^[13]). Although some metals occur naturally in marine sediments, high concentrations of metals above the guideline value or the presence of toxic metals such as mercury and cadmium can indicate anthropogenic sources of contamination at specific locations. Guideline values for each metal were developed based on a review of international best practices for sediment quality criteria and of historical data collected by EAD from the marine protected areas (MPAs) in the Western Region of Abu Dhabi.

Based on the long-term marine water quality data, EAD developed ambient marine water and sediment quality standards in 2017 (ADQCC17a-2017^[01]). Two types of standards were developed in Abu Dhabi Emirate: one for MPA and other for general use. In MPAs, the “Protected Area” designated use has been applied along with more protective threshold values to support that use. For all other waters, the “General Use” has been applied. The recommended standards for General Use waters are those from the best international practices that are most protective of marine life and also account for the levels of metals found in the emirate’s marine water column and sediments.

Table 5. Marine Sediment Heavy metal threshold/standards followed by different Countries

Heavy Metals	Vol- Development and Evaluation of sediment Quality Assessment guidelines Nov-1994 Mac Donald, Florida	Environment Standards EPA 1986	Canadian Environment Quality Guidelines	Water Quality guidelines & standards in marine environment -UK	Ambient Marine Sediment quality standards – Environment Agency Abu Dhabi
Cadmium (mg/kg)	0.68	5.1	4.2	4.2	0.68
Chromium (mg/kg)	52.3	260	160	160	52.3
Cobalt (mg/kg)	-	-	-	-	-
Copper (mg/kg)	18.7	390	108	108	18.7
Lead (mg/kg)	30.2	450	112	112	30.24
Manganese (mg/kg)	-	-	-	-	-
Nickel (mg/kg)	15.9	-	-	-	15.9
Zinc mg/kg)	124	410	271	271	124
Mercury (mg/kg)	0.41	0.41	0.7	0.7	0.13
Iron (mg/kg)	-	-	-	-	-

Table 6. Distribution of heavy metals in marine sediment worldwide

Location	Cu	Cd	Cr	Co	Pb	Ni	Mn	Zn	Fe	Unit	References
U.A. E											
Barakah, Abu Dhabi	1.17	0.03	5.3	0.5	1.4	4.3	30	3.2	1339	ppm	Al Rashdi et al. (2017) ^[4]
Abu Dhabi	4.65	0.08			1.91	10.55	92.26	11.94	2800	(µg g ⁻¹)	El Tokhi et al. (2017) ^[22]
Abu Dhabi	1.99	0.02	17.6	0.34	0.78	2	32.9		874	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Al Marfa	3.58	0.11	37.6	2.61	2.93	15.5	225		5820	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Al Ruwais	2.62	0.11	171	2.4	5.88	8.6	358		8940	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Um Al Quwain	5.03	0.21	71.9	3.3	2.54	25	231	3.4	6055	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Jebel Ali	1.92	0.05	31.7	1.16	2.1	8.3	96.6		2740	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Qatar -Umm Said	8.17	0.09	31.9	1.96	3	17.1	84.9		4790	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Qatar -Doha	8.02	0.08	40.8	2.2	3.16	20.8	88		5680	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Bahrain - East Coast Askar	1.95	0.19	9.86	1.12	11	16	21.2	2.34	3441	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Oman Gulf, UAE	9	5.02	156.57	24.46	11.62	497.46	254.85	17.16	21469.9	ppm	El Tokhi et al. (2017) ^[22]
Oman - Muscat (Mutrah-Daraayt)	10.4	0.18	357	22.1	6.79	43.9	310	26.3	22749	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Oman -Salalah (Raysut)	9.99	0.7	116	5.33	25.9	34.6	181	24.5	11369	(µg g ⁻¹)	De Mora et al. (2004) ^[19]
Kuwait - Sulaibikhat Bay	36.7		140	17.4	10.5	97.8		93.3		mg/kg	Al Shemmari et.al. (2010) ^[06]
Saudi Arabia -Ras Al Khafji	3.24	0.14	32	1.38	1.7	13.8	41.9	3.41	5454	µg g ⁻¹	De Mora et al. (2004) ^[19]
Red Sea - Gulf of Aqaba	0.03	5.25	1.12		4.07	0.43		0.42		(µg g ⁻¹)	Al Najjar et.al. (2011) ^[08]
ROPME-RSA	5	0.2	115.2	5.3	3.7	74.2	166	8.9	8200	(µg g ⁻¹)	ROPME - SMER.2013 ^[48]
Egypt - Mediterranean Sea Coast-Egypt			0.26		405.71	803.03	614.06	340.23	193791.18	(µg/g)	El Sorogy.et.al. (2015) ^[21]
Yemen - Al-Hodeidah, Yemen	11.3	14.2	20.2		3.48	13.25		30		(µg g ⁻¹)	Al Adrise (2002) ^[03]
India -West Coast	84	0.41	163	23	20	69	1025	107	733114	(mg/kg)	Kumar.et.al. (2013) ^[34]
India - Pondicherry/Bay of Bengal	47.74	2.76	333.55		32.91	19.72	235.35	52.04		(µg/g)	Solai et al. (2013) ^[53]
Indonesia -Telaga tujuh coast	46.3				88.2			96.8		(mg/kg)	Amin (2002) ^[11]
Yellow sea (Summer)	15.1	0.513		8.24	12.3	18.6	410	47.3	0.0133	(µg/g)	Xin Jiang et al. (2014) ^[63]
Yellow sea (winter)	15.9	0.115		8.46	11.3	18.8	373	46.2	0.0136	(µg/g)	Xin Jiang et al. (2014) ^[63]
Turkey - Black Sea	52.1	ND		15.8	22.1	67.7	621	82.4	0.0272	(µg/g)	Kiratli and Ergin (1996) ^[32]
Germany - Bremen Bay	87		131		122	60		790		(mg/kg)	Pekey (2006) ^[45]
Malaysia - Coastal Area of Tuaran, Sabah	6.49	0.4	3.81		2.63			22.03		(mg/kg)	Wei Hsiang et al. (2016) ^[60]

These promulgated ambient limits were then used to develop the marine water and sediment regulation that established two uses of marine waters (protected and general) and an anti-degradation policy. Furthermore, the ambient water and sediment limits provide a benchmark for

both assessment trends that may indicate stress to marine flora and fauna and support the work of environmental permitting and enforcement. Additionally, as part of pollution abatement and to support ecologically and socially sustainable development, EAD developed specifications for land base liquid discharges in the marine environment (ADQCC 17b-2017^[02]).

Environmental Impact Assessment (EIA) is one of the important processes included in all developmental projects in Abu Dhabi to identify the impacts of the project to prevent and reduce pollution, including heavy metal pollution. Environmental permitting and licensing is another way of controlling pollution in the marine environment. Frequent inspection and stringent standards in the industries reduce and control the inflow of pollutants in the marine environment. Moreover, the EAD created and stood up a special unit for responding to pollution emergencies and has developed programs for disseminating pollution awareness to the public.

4 Conclusion

The present study highlights the importance of heavy metal distribution in Abu Dhabi's territorial waters, including offshore. The distribution pattern significantly varied spatially, and high concentrations were recorded in many areas in the offshore waters. The present study confirms that the distribution of heavy metals in the marine sediments of Abu Dhabi waters is mainly influenced by the bottom topography (bathymetry), depth, current patterns, and sediment nature. Various indices and statistical analyses revealed that the metal concentrations in Abu Dhabi waters were not at the polluted level and that most of them were within international standards. Higher metal concentrations in Western Region waters could stem from trans-boundary pollution. Protection strategies aimed at regional preventive and curative activities in coordination with other Arabian Gulf coast-sharing countries should be developed. As the Arabian Gulf water is shared by many countries, no actions taken by a single country will be effective in controlling pollution. Trans-boundary pollution can be properly managed only by combined efforts of the Arabian Gulf countries. Therefore, there is a critical need for a holistic approach to monitor heavy metal concentrations and distributions and a comprehensive strategy to combat and manage heavy metal pollution.

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REFERENCES

- [1] ADQCC (Abu Dhabi Quality and Conformity Council), 2017a. Ambient Marine Water and Sediments specifications, pp15. Available at:
[https://qcc.abudhabi.ae/en/PublicationsStandards/ADS%20Ambient%20Marine%20Standards%2020170510%20\(003\)](https://qcc.abudhabi.ae/en/PublicationsStandards/ADS%20Ambient%20Marine%20Standards%2020170510%20(003)).

- [2] ADQCC (Abu Dhabi Quality and Conformity Council), 2017b. Environmental Specifications for land based liquid discharge to the marine environment, 15. Available at: <https://qcc.gov.ae/-/media/Project/QCC/QCC/Documents/Quality-Infrastructure-Documents/Abu-Dhabi-Specification/Abu-Dhabi-Specifications/ADS-23>
- [3] Al Adrise, M.A.M., 2002. Concentration of some heavy metals in Khor-Kutheb Area (Al-Hodiedah) as a result of the sewage effluent impacts. MSc Thesis. Hodeida University.
- [4] Al Rashdi, M.R., Alaabed, S., El Tokhi, M., Howari, F. M., El Mowafi, W., Arabi, A.A., 2017. Distribution of heavy metals around the Barakah nuclear power plant in the United Arab Emirates. Environ. Sci .Pollut .Res. DOI 10.1007/s11356-017-9353-2.
- [5] Al Rashdi, S., Arabi, A.A., Howari, F.M., Said, A., 2015. Distribution of heavy metals in the coast of Abu Dhabi in the United Arab Emirates. Mar. Pollut. Bull. 97: 494-498.
- [6] Al Shemmari, H., Yousef, A., Ronan, O., 2010. Trace metal concentration in the surface sediments of Sulaibikhat Bay Kuwait. Kuwait J. Sci & Eng 37(2A):pp87-110 .
- [7] Alba, M.D., Galindo-Riano, M.D., Casanueva-Marenco, M.J., Garcí'a-Vargas, M., Kosore, C.M., 2011. Assessment of the metal pollution, potential toxicity and speciation of sediment from Algeciras Bay (South of Spain) using chemo metric tools. Journal of Hazardous Materials 190: 177–187.
- [8] Al-Najjar, T., 2011. Heavy metals pollution in sediment cores from the Gulf of Aqaba, Red Sea. Natl. Sci. 3 (9), 775—782, [http://dx. doi.org/10.4236/ns.2011.39102](http://dx.doi.org/10.4236/ns.2011.39102).
- [9] Alosairi Y., Pokavanich T., 2017. Seasonal circulation assessments of the Northern Arabian/Persian Gulf. Mar. Pollut. Bull. 15;116 (1-2):270-290.
- [10] Aloupi, M., Angelidis, M.O., 2001. "Geochemistry of natural and anthropogenic metals in the coastal sediments of the island of Lesbos, Aegean Sea," Environmental Pollution, vol. 113, no. 2, pp. 211–219.
- [11] Amin, B., 2002. Distribution of heavy metals Pb, Cu and Zn in surface sediments at Telaga Tujuh Karimun, Riau Archipelago. J. Nat. Indonesia 5: 9–16.
- [12] Amin, B., Ismail, A., Yap, C.K., Kamarudin, M.S., 2009. Anthropogenic impacts on heavy metal concentrations in the coastal sediments of Dumai, Indonesia. Environ. Moni. Assess. 148: 201-305.
- [13] ATSDR (Agency for Toxic Substances and Disease Registry). (2016). Priority List of Hazardous Substances. Available at: <https://www.atsdr.cdc.gov/spl/>
- [14] alachandran, K. K., Laluraj, C. M., Nair, M., Joseph, T., Sheeba, P., Venugopal, P., 2005. Heavy metal accumulation in a flow restricted, tropical estuary. Estuarine, Coastal and Shelf Science, 65, 361–370.
- [15] Birch, G.F., Taylor, S.E., Matthai, C., 2001. Small-scale spatial and temporal variance in the concentration of heavy metals in aquatic sediments: a review and some new concepts. Environ. Pollut. 113: 357–372.
- [16] Caeiro, S.M.H., Costa, T.B., Ramos, F., Fernandes, N., Silveira, A., Coimbra, G., Medeiros, M., Painhoe, M., 2005. Assessing heavy metal contamination in Sado Estuary sediment: An index analysis approach Ecological Indicators 5 151–169.

- [17] CCME (Canadian Council of Ministers of the Environment). 2001. Canadian Water Quality Guidelines for the Protection of Aquatic Life: CCME Water Quality Index 1.0 Technical Report. Available at: [http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20\(en\).](http://www.ccme.ca/files/Resources/calculators/WQI%20User's%20Manual%20(en).)
- [18] Chakravarty, M., Patgiri, A.D., 2009. Metal pollution assessment in sediments of the Dikrong River, NE India," J. Hum. Ecol., 27 (1), pp. 63-67.
- [19] De Mora, S., Fowler, S., Wyse, E., Azemard, S., 2004. "Distribution of Heavy Metals in Marine Bivalves, Fish and Coastal Sediments in the Gulf and Gulf of Oman," Mar. Pollut. Bull. Vol. 49, pp. 410-424.
- [20] El Nemr, A.M., Sikaily, A.E., Khaled, A., 2007. Total and leachable heavy metals in muddy and sandy sediments of Egyptian coast along Mediterranean Sea. Environ. Moni. Assess. 129:151–68.
- [21] El Sorogy, A., Tawfik, M., Almadani, S., Attiah, A., 2015. Assessment of toxic metals in coastal sediments of the Rosetta area, Mediterranean Sea. Egypt. Environ. Earth. Sci. 75, 398.
- [22] El Tokhi, M., Amin, B.M., Alaabed, S.A., 2017. Environmental Assessment of Heavy Metals Contamination of Bottom Sediments of Oman Gulf, United Arab Emirates. J Pollut Eff Cont. (open access journal). Volume 5 • Issue 4 • 1000203.
- [23] Fergusson, J.E., 1990. The Heavy Elements: Chemistry, Environmental Impact and Health Effects. Oxford: Pergamon Press.
- [24] Foda, M. A., Khalaf, F., Al- Khadi, A., 1985. Estimation of dust fallout and rates in the northern Arabian Gulf, Sedimentology, 32: 595-603.
- [25] Fowler, S.W., 1985. Coastal baseline studies of pollutants in Bahrain, UAE and Oman ROPME Symposium on Regional Marine Monitoring and Research Programs UAE University, Al-Ain, UAE.
- [26] Fytianos, K., Laurantou, A., 2004. Speciation of elements in sediment samples collected at lakes Volvi and Koronia, N. Greece. Environ Int 30: 11–17.
- [27] Grousset, F.E., Quetel, C.R., Thomas, B., Donard, O.F.X., Lambert, C.E., Guillard, F., Monaco, A., 1995. Anthropogenic vs. lithogenic origins of trace elements (As, Cd, Pb, Rb, Sb, Sc, Sn, Zn) in water column particles: northwestern Mediterranean Sea. Marine Chemistry 48, 291e310.
- [28] Hakanson, L., 1980. An Ecological Risk Index for Aquatic Pollution Control. A Sedimentological Approach. Water Research, 14, 975-1001.
- [29] Halpern, B., Walbridge, S., Selkoe, K., Kappel, C., Micheli, F., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.
- [30] Herut, B., Hornung, H., Krom, M.D., Kress, N., Cohen, Y., 1993. Trace metals in shallow sediments from the Mediterranean coastal region of Israel. Mar. Pollut. Bull., 26: 675-682.
- [31] Kim, K.T., Kim, E.S., Cho, S.R., Park, J.K., Ra, K.T., Lee, J.M., 2010. Distribution of Heavy Metals in the Environmental Samples of the Saemangeum Coastal Area, Korea. Coastal Environmental and Ecosystem Issues of the East China Sea, Eds., A. Ishimatsu and H.-J. Lie, pp. 71–90.

- [32] Kirtli, N., Ergin, M., 1996. Partitioning of heavy metals in surface Black Sea sediments. *Applied Geochemistry*, 11(6), 775–788. doi: 10.1016/S0883-2927(96)00037-6.
- [33] Krumgalz, B.S., Fainshtein, G., Cohen, A., 1992. 'Grain Size Effect on Anthropogenic Trace and Organic Matter Distribution in Marine Sediments', *Sci. Total Environ.* 116, 15–30.
- [34] Kumar, G., Ramanathan, A.L., 2013. Geochemical Assessment of Heavy Metal Contamination in Mangrove Ecosystem: A Brief Overview. *Int. Res. J. Environ. Sci.* Vol. 2(3), 62-66, March.
- [35] Li, X., Liu, L., Wang, Y., Luo, G., Chen, X., et al., 2012. Integrated Assessment of Heavy Metal Contamination in Sediments from a Coastal Industrial Basin, NE China. *PLOS ONE* 7(6): e39690. doi:10.1371/journal.
- [36] Loomb, C.A.M., 2001. Muddy sedimentation in a sheltered estuarine marine, Westpark Marina, Auckland, New Zealand. Thesis, the University of Waikato.
- [37] Loska, K., Wiechula, D., Barska, B., Cebula, E., Chojnecka, A., 2003. Assessment of arsenic enrichment of cultivated soils in Southern Poland," *Pol. J. Environ. Stud.*, 12 (2), pp. 187– 192.
- [38] Luoma, S.N., 2000. Processes Affecting Metal Concentrations in Estuarine and Coastal Marine Sediments, in R. W. Furness & P. S. Rainbow (ed.), *Heavy Metals in the Marine Environment*, CRC Press, Inc, Florida, USA, 51- 66.
- [39] Manta, D.S., Angelone, M., Bellanca, A., Neri, R., Sprovieri, M., 2002. Heavy metals in urban soils: a case study from the city of Palermo (Sicily), Italy. *The Science of the Total Environment* 300: 229–243.
- [40] Muller, G., 1969. Index of Geoaccumulation in Sediments of the Rhine River, *Geo. jour.* 2(3), 108-118.
- [41] Muller, G., 1981. The Heavy Metal Pollution of the Sediments of Neckars and Its Tributary, A Stocktaking *Chemische Zeit*, 150, 157-164.
- [42] Naser, H., 2012. Metal Concentrations in Marine Sediments Influenced by Anthropogenic Activities in Bahrain, Arabian Gulf. In: Hong-Bo, Shao (Ed.), *Metal Contaminations: Sources, Detection and Environmental Impacts*. NOVA Science Publishers, Inc., New York, pp. 157–175.
- [43] Naser, H.A., 2013. Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. *Mar. Pollut. Bull.* 72:6–13.
- [44] Ong, M.C., Kamaruzzaman, B.Y., 2009. An assessment of metal (Pb and Cu) contamination in bottom sediments from South China Sea coastal waters, Malaysia," *Am. J. Appl. Sci.*, 6 (7): pp. 1418-1423.
- [45] Pekey, H., 2006. The distribution and sources of heavy metals in Izmit Bay surface sediments affected by a polluted stream. *Mar. Pollut. Bull.* 52: 1197-1208.
- [46] Prosi, F., VanLierde, J.H., 1979. Metal pollution in the aquatic environment. Springer-Verlag-New York.
- [47] Purser, B.H., Seibold, E., 1973. The principal environmental factors influencing Holocene sedimentation and diagenesis in the Persian Gulf. In the Persian Gulf ed. B.H. Purser. Springer, New York, USA, pp. 1-9.

- [48] ROPME 2013. State of the Marine Environment Report- 2013. ROPME/ GC-16 /1-ii Regional Organization for the Protection of the Marine Environment, Kuwait, 225 p.
- [49] ROPME, 2005.Guidelines for management of industrial wastewater for the ROPME region, Kuwait.
- [50] SCAD (Statistics Centre–Abu Dhabi). 2016. Statistical Yearbook of Abu Dhabi 2016. Abu Dhabi, United Arab Emirates. Available at:

<https://www.scad.ae/en/Pages/ThemesReleases.aspx?ThemeID=1&SubThemeID=1>
- [51] Seshan, B.R.R., Natesan, U., Deepthi, K., 2010. Geochemical and statistical approach for evaluation of heavy metal pollution in core sediments in southeast coast of India,” Int. J. Environ. Sci. Tech., 7 (2), pp. 291-306.
- [52] Simex, S.A., Helz, G.R., 1981. Regional geochemistry of trace elements in Chesapeake Bay. Environ. Geol., 3(6), 315–323.
- [53] Solai, A., Ghandi, M.S., Kasilingam, K., Sriraman, E., 2013. Heavy Metal Accumulation in the Surface Sediments off Pondicherry, Bay of Bengal, South East Coast of India. IJRSET. Vol. 2, (10) 5741-5753.
- [54] Sollitto, D., Romic, M., Castrignano, A., Romic, D., Bakic, H., 2010. Assessing heavy metal contamination in soils of the Zagreb region (Northwest Croatia) using multivariate geostatistics. CATENA 80: 182–194.
- [55] Sutherland, R.A., 2000. Bed sediment associated trace metals in an urban stream Oahu. Hawaii,” Environ. Geo., 39 (6), pp. 611-627.
- [56] Tam, N.F.Y., Wong, Y.S., 2000. Spatial variation of heavy metals in surface sediments of Hong Kong mangrove swamps. Environ. Pollut. 110: 195-205.
- [57] Tan, W.H., Tair, R., Ali, S.A.M., Talibe, A., Sualin, F., Payus, C., 2016. Distribution of Heavy Metals in Seawater and Surface Sediment in Coastal Area of Tuaran, Sabah. Transactions on Science and Technology. 3 (1-2), 114 – 122.
- [58] Tomlinson, D.L., Wilson, J.G., Harris, C.R., Jeffney, D.W., 1980. Problems in the Assessment of Heavy-Metal Levels in Estuaries and the Formation of a Pollution Index. Helgoland Marine Research, 33(1-4), 566-72.
- [59] Turekian, K. K., Wedepohl, K.H., 1961. “Distribution of the elements in some major units of earth's crust,” Bull. Geol. Soc. Am., 72, pp.175-192.
- [60] Wei Hsiang, T., Rohana, T., Siti, A., Mohd, A., Asdalifah, T., Fatin, S., Carolyn, P., 2016. Distribution of heavy metals in seawater and surface sediment in coastal area of Tuaran, Sabah. Transactions on Science and Technology, 3 (1-2). pp. 114-122. ISSN 2289-8786.
- [61] Williamson, B., Har, N., Purvis, W., Rusu, A. M., 2003. Preliminary studies of airborne particulate emissions from the Ampellum S. A. copper smelter, Zlatna, Romania, Studia Universitatis, “Babes Bolyai”48, 1, 67-76.

- [62] Williamson, R.B., Wilcock, R.J., 1994. The Distribution and fate of contaminants in estuarine sediments: recommendations for environmental monitoring and assessment, Technical Publication, 47, New Zealand.
- [63] Xin Jiang, Ankang Teng, Wenzhe Xu and Xiaoshou Liu, 2014. Distribution and pollution assessment of heavy metals in surface sediments in the Yellow Sea. Mar. Pollut. Bull. 83, 366-375.
- [64] Zhang, J., Liu, C. L., 2002. Riverine composition and estuarine geochemistry of particulate metals in China - weathering features, anthropogenic impact and chemical fluxes. Estuar. Coast. Shelf S. 54, 1051–1070.