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A Comprehensive Assessment of Metal Pollution and Ecological Risk in the Marine Sediments of Izmir Bay

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Abstract: This study provides a comprehensive assessment of metal and metalloid contamination in the surface sediments of Izmir Bay, Eastern Aegean Sea. Surface sediments were collected from ten stations across different sub-regions of the bay and analyzed for concentrations of Cd, Pb, Cu, Zn, Ni, Cr, Mn, As, and Hg, along with grain size distribution and total organic carbon (TOC) content. Several geochemical and ecological risk indices, including the Geoaccumulation Index (Igeo), Pollution Load Index (PLI), Potential Ecological Risk Index (PERI), and Sediment Quality Guidelines (SQGs), were applied to evaluate contamination levels and ecological risks. The results revealed higher metal concentrations in the inner bay, coinciding with elevated TOC and finer sediments, while the outer bay exhibited comparatively lower levels. Cd, Pb, and Cu were identified as the main pollutants exceeding natural background values, with industrial and domestic inputs as the dominant sources. Risk indices further indicated that Cd and Pb posed the greatest ecological threat, particularly at stations affected by urban wastewater discharge and port activities. Overall, the findings highlight the combined influence of natural and anthropogenic processes on metal accumulation and provide critical baseline information for future monitoring and management strategies in Izmir Bay.

Keywords: Metal contamination, surface sediments, izmir bay, ecological risk assessment.

İzmir Körfezi Deniz Sedimentindeki Metal Kirliliği ve Ekolojik Riskin Kapsamlı Bir Değerlendirmesi

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Öz: Bu çalışma, Doğu Ege Denizi, İzmir Körfezi'ndeki yüzey sedimanlarındaki metal ve metaloid kirliliğinin kapsamlı bir değerlendirmesini sunmaktadır. Körfezdeki farklı alt bölgelerdeki on istasyondan yüzey sedimanları toplanmış ve Cd, Pb, Cu, Zn, Ni, Cr, Mn, As ve Hg konsantrasyonları, tane boyutu dağılımı ve toplam organik karbon (TOC) içeriği açısından analiz edilmiştir. Jeoakümülasyon İndeksi (Igeo), Kirlilik Yükü İndeksi (PLI), Potansiyel Ekolojik Risk İndeksi (PERI) ve Sediment Kalitesi Kılavuzları (SQG'ler) dahil olmak üzere çeşitli jeokimyasal ve ekolojik risk endeksleri, kirlenme seviyelerini ve ekolojik riskleri değerlendirmek için uygulanmıştır. Sonuçlar, iç körfezde yüksek metal konsantrasyonlarının, yüksek TOC ve daha ince sedimanlarla çakıştığını ortaya koyarken, dış körfezde nispeten daha düşük seviyeler sergilemiştir. Cd, Pb ve Cu, doğal arka plan değerlerini aşan ana kirleticiler olarak tanımlanmış olup, baskın kaynaklar endüstriyel ve evsel girdilerdir. Risk endeksleri ayrıca, özellikle kentsel atık su deşarjı ve liman faaliyetlerinden etkilenen istasyonlarda Cd ve Pb'nin en büyük ekolojik tehdidi oluşturduğunu göstermiştir. Genel olarak, bulgular doğal ve antropojenik süreçlerin metal birikimi üzerindeki birleşik etkisini vurgulamakta ve İzmir Körfezi'nde gelecekteki izleme ve yönetim stratejileri için kritik temel bilgiler sağlamaktadır.

Anahtar Kelimeler: Metal kirliliği, yüzey sedimanları, izmir körfezi, ekolojik risk değerlendirmesi.

INTRODUCTION

Metals and metalloids (Chapman & Holzmann, 2007) are major inorganic pollutants in seawater and marine sediments. Metal and metalloid concentrations have been accepted for many years to accumulate in the marine environment from natural (surface runoff, atmospheric deposition, river discharges) and anthropogenic sources (industrial and domestic wastewater, agricultural activities, vehicle emissions) sources. To identify where pollution problems come from, it is necessary to separate natural sources from anthropogenic sources (Ergin et al., 1991; Esen et al., 2010).

Anthropogenic pollution, stemming primarily from industrialization, urbanization, and agricultural intensification in coastal and riverine areas, results from the discharge of untreated or inadequately treated wastewater into water bodies. These activities introduce significant amounts of toxic metals into marine ecosystems, which then accumulate in sediments, increasing the risk of long-term environmental degradation (Vosoogh et al., 2016; Liu, Wang et al., 2019).

Dissolved metals mixed into the sea from various sources are adsorbed on particles in seawater and go from the water column to the bottom sediments. Since metals found in bottom sediments are more easily adsorbed in fine-grained sediments rich in clay minerals, metal concentration increases in sediments with small grain sizes. In this context, it is important to monitor sediment quality (Esen et al., 2010). Sediment quality is a comprehensive concept that includes the physical, chemical, and biological properties of sediments in aquatic environments.

The behavior of metals in sediments plays a crucial role in environmental risk assessments, as metals do not exist in soluble forms in aquatic environments but typically accumulate in sediments, potentially leading to long-term ecological effects. In this context, metal accumulation in sediments follows dynamics distinct from those of water quality (Wasserman et al., 2013). Thus, sediments serve as both a reservoir and a source for metal pollution (Özşeker & Terzi, 2025).

Metal pollution is one of the most persistent and concerning issues affecting both marine and freshwater ecosystems, primarily due to its toxicological effects and environmental persistence (Madesh et al., 2024). As toxic metals settle into sediments, numerous biochemical reactions occur, leading to the transfer of these metals from pore water into the deep-sea water. Consequently, the geochemistry of the bottom sediments directly influences the chemistry of the water column. Heavy metals accumulated in contaminated sediments therefore pose a toxic threat not only to benthic organisms but also to organisms residing in the water column (Özseker, 2021).

While metals such as iron (Fe), cobalt (Co), and zinc (Zn) can be beneficial to marine organisms, Cd, Pb, Hg, As, and Cu pose significant ecological risks due to their persistence and tendency to accumulate in aquatic sediments, and they may be remobilized under changing environmental conditions (Feng et al., 2011; Saiful et al., 2015). As a result, metals can enter the food chain and negatively affect human health and ecosystems (Tan & Aslan, 2020).

Monitoring of inorganic and organic pollutants in terms of seawater quality is important in evaluating the ecosystem as a whole. These metals are evaluated by various methods according to the Sediment Quality Guidelines (SQGs) (Long & MacDonald, 1998). Various institutions in North America have established these guidelines to assess the ecological risks of metals and the degree of single or overall pollution to freshwater and marine ecosystems.

Heavy metal concentrations play a central role in assessing sediment quality. Anthropogenic activities stemming from industrial and urban areas, particularly in coastal and riverine zones, lead to the accumulation of toxic metals such as arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni), and lead (Pb), highlighting the need for continuous regional monitoring (Veerasingam et al., 2025).

The physical properties of sediments, namely grain size and total organic carbon (TOC), are critical parameters that determine metal bioavailability. Fine-grained sediments, with their larger surface area, provide more binding sites for metals, leading to higher concentrations. Similarly, elevated TOC levels influence metal complexation, affecting their mobility and biological accessibility. As a result, grain size and TOC are decisive in controlling metal concentrations and their bioavailability (Koskey et al., 2020).

The most critical chemical parameter controlling metal behavior in sediments is pH. Low (acidic) pH levels increase metal solubility, thereby enhancing their bioavailability. For example, metals like arsenic and cadmium become more mobile under acidic conditions, posing a potential toxicity risk to benthic organisms.

Human activities directly impact sediment quality and ecosystem health. Operations like dredging in ports can remobilize accumulated metals such as Pb, Cu, and Zn into the water column, increasing their mobility and elevating the risk of environmental degradation (Montigly et al., 2025).

Industrial and urban effluents increase metal accumulation in coastal sediments. Particularly in densely industrialized ports, metals such as Cd, Ni, and Pb are found at elevated concentrations. A study on 47 rivers in Poland revealed that industrial discharges and urban runoff led to the accumulation of high levels of toxic metals such as Cu, Pb, Cd, Cr, Ni, and Zn in sediments (Sojka & Jaskuła, 2022).

The primary aim of this study is to assess the ecological risks and pollution levels of metals and metalloids in surface sediments of Izmir Bay, while also identifying the impacts of natural and anthropogenic sources. The relationships between sediment physical property (grain size) and metal accumulation were examined to investigate the sediment's metal retention capacity and bioavailability. Furthermore, contamination levels and potential ecological risks were evaluated using geo-accumulation index (Igeo), potential ecological risk index (PERI) pollution load index (PLI), and sediment quality guidelines (SQGs). This comprehensive approach aims to reveal the current status of toxic metal pollution in Izmir Bay and to provide a scientific basis for future monitoring and pollution mitigation strategies.

MATERIAL AND METHOD

Study Area: Izmir Bay, one of the largest bays in the Mediterranean, is located along the coastal regions of Izmir Province in Türkiye, between the coordinates of 38° 32′ 9″ North and 26° 45′ 17″ East (Fig. 1). The bay covers a total surface area exceeding 500 km², with a water capacity of approximately 11.5 billion m³. It is divided into three sections: the outer bay, the middle bay, and the inner bay. The inner bay, the smallest and shallowest part (57 km²), is more affected by anthropogenic activities due to its proximity to urban and industrial areas (Duman et al., 2004).

The middle bay, approximately 10 km long, is separated from the inner bay by the Yenikale Strait, a very narrow channel with a depth of 13 m. This shallow passage was formed over the last few centuries due to delta shifts of the Gediz River along the Pelikan and Karşıyaka coasts. The water depth in the inner bay is generally less than 15 m (Başoğlu 1975; Özkan & Büyükışık 2008).

The primary current observed in Izmir Bay is a cyclonic (counterclockwise) circulation encompassing the entire bay. This circulation is influenced by atmospheric forces such as wind and water exchange with the Aegean Sea. Currents in the inner bay are generally weak and show limited variability. The inner bay currents form a cyclonic loop constrained by the bay's geometric structure and bottom topography. As waters exit the inner bay, they tend to move outward, but these currents remain generally weak (Beşiktepe et al., 2011; Talas et al., 2023).

Rapid population growth, industrial development, and the presence of Türkiye's oldest commercial port have led to uncontrolled land development around Izmir Bay, causing environmental degradation and pollution. The bay is heavily influenced by chemical inputs from rainfall, urban wastewater, agricultural activities, and other sources (Küçüksezgin et al., 2005; Yelekci et al., 2020). Domestic wastewater is a significant source, as it is discharged into the Inner and Outer Bays via streams into the Gediz River (Atgin et al., 1999). Izmir Bay is also home to Alsancak Port, which contributes to industrial activities and maritime transportation. Industrial facilities and the Gediz River are the primary contributors to metal contamination in sediments (Serifaki, 2006). This complex interaction makes Izmir Bay an important area for studying metal pollution and its ecological implications.

Many industries (food processing, chemical industries, oil, soap and paint production, paper and pulp mills, textile industries, and metalworking) located along the shores of the streams and catchment basins flowing into Izmir Bay discharge organic and inorganic pollutants into the rivers, resulting in sediment and water pollution in the bay (Güven et al., 2007). In particular, there are nearly 20 small rivers (old Gediz, Bostanlı, Bayraklı, Manda, Arap, Melez, Bornova, Poligon & Ilıca) flowing into the inner Bay (Atgin et al., 1999). In 2000, with the establishment of the Izmir Bay Grand Canal Project, all wastewater was directed to the advanced biological treatment facilities in Urla (Güzelbahçe) (Qavg = 21,600 m³/day) and Çiğli (Qavg = 604,800 m³/day) (Fig. 1). The treatment plants located in the north and south prevented uncontrolled wastewater discharge into the bay, ensuring that the treated wastewater was discharged into the bay (İZSU, 2022).

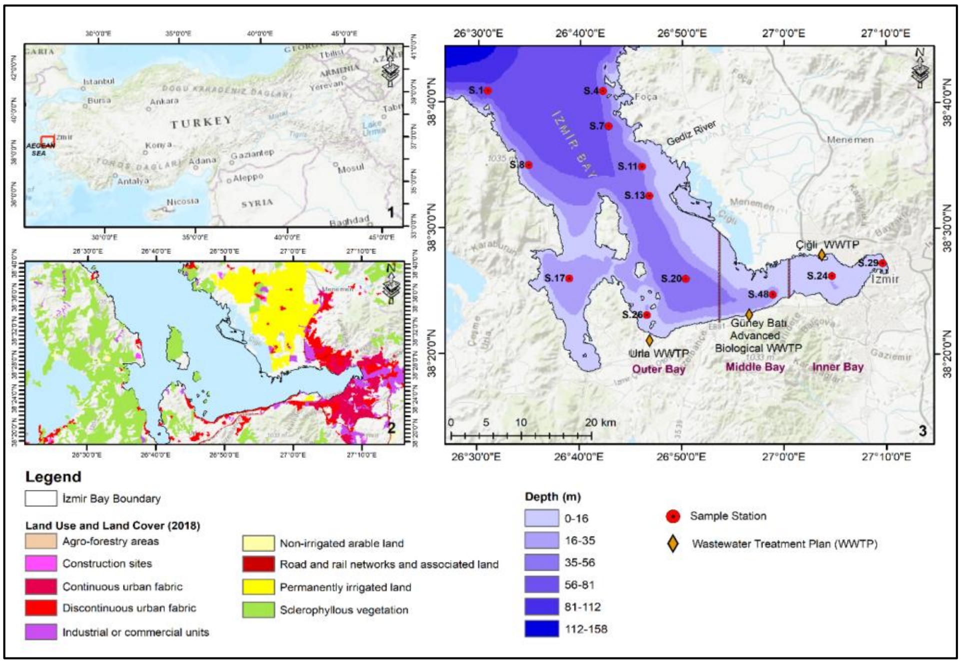

Figure 1. Land use of the eastern part of the Izmir Bay and the sampling locations (1) Türkiye, (2) Land use land cover, (3) Sample location and depth.

Sample Collection and Analyses: In order to represent different regions of Izmir Bay and the pressures on them, 12 sampling stations with depths ranging from 4 to 77 m were identified in May 2021 (Fig. 1). The field surveys and sampling were conducted on board the R/V TÜBİTAK MARMARA, a medium-sized oceanographic research vessel operated by TÜBİTAK Marmara Research Center.

The selection of sampling stations was based on the discharge points of agricultural areas, oil processing plants, and wastewater treatment facilities. Sediments for sampling were collected using a Van Veen grab sampler (0.1 m^2). The upper 2–3 cm of the sediment was taken with a polyethylene spoon to prevent contamination. Subsequently, sediments were stored in clean polyethylene bags for grain size analysis, and in glass bottles for TOC and metal analyses. The glass bottles containing sediments were kept at −20°C until further processing. Grain size analysis was conducted according to Folk (1974). The water content of the sediments was determined using an AND MX-50 Moisture Analyzer. Since metals generally accumulate in the fine sediment fraction (Salomons & Förstner, 1984), wet samples were sieved through a 63 µm mesh. The samples were freeze-dried and homogenized using a mortar grinder (Retsch RM200). For TOC analysis, 2–3 spoons of dried sediment were placed in a crucible. A 1:1 HCl: water solution was then added and left until gas release ceased. The HCl: water mixture was removed under vacuum, and after several washings with distilled water, the sediments were dried overnight at 55°C. The TOC content of the dried sediment samples was determined using a CHNS analyzer (Thermo Finnigan Flash EA 1112 Series). For metal analysis, a modified EPA-3052 method was applied. Approximately 0.1 g of dried, homogenized sediment was placed in a closed Teflon vessel containing 4 mL HNO_3 (Merck, Darmstadt, Germany), 2 mL HCl (Merck, Darmstadt, Germany), and 1 mL HF (Merck, Darmstadt, Germany) for complete digestion. The digestion was carried out using a microwave acid digestion system (Milestone Ultrawave) at 120°C for 35 minutes. After cooling, about 0.3 g of boric acid was added to complex fluorides and protect the quartz plasma torch from excess hydrofluoric acid. The same microwave digestion procedure was then repeated. After cooling, the vessel contents were filtered and diluted to 50 mL with deionized water. The diluted samples were stored in polyethylene bottles for analysis. The solutions and blanks were analyzed for metals (Al, Fe, As, Cd, Cu, Cr, Ni, Pb, Zn) using ICP-MS (Perkin Elmer Nexion 300x). The total mercury (Hg) content of dried sediment samples was determined using a Milestone DMA-80 Direct Mercury Analyzer. The accuracy and precision of analytical procedures were verified by analyzing a certified reference marine sediment, IAEA-158 (Campbell et al., 2008). TOC in seawater and sediment is conducted to determine the amount of organic compounds present. This analysis not only serves as an indicator of water cleanliness but is also related to the growth rates of endotoxins and microbes. The accuracy and precision of the metal analysis procedures have been checked by using a certified reference material marine sediment IAEA-158 (Campbell et al., 2008) (Table 1).

Table 1. Results indicate good compatibility between the certified and found values

Element	Certified Value	Standard Deviation	Found Value	Recovery (%)
Al	51.800	3.400	50.794	98
Fe	26.300	1.400	25.999	99
As	11.5	1.2	11.8	103
Cd	0.372	0.039	0.371	100
Cr	74.4	5.8	72.3	97
Cu	48.3	4.2	51	105
Ni	30.3	2.9	30.2	100
Pb	39.6	4.7	39.3	99
Zn	140.6	9.5	138.7	99
Hg	0.132	0.014	0.1318	100

Contamination Status: In this study, sediment samples were collected from various locations on a large scale to clarify the spatial distribution characteristics of metals . In the assessment of metals, they are generally categorized into two main groups: essential and toxic metals. Essential metals are those required by organisms and must be present in specific concentrations (e.g., Fe, Zn, Cu). Toxic metals, on the other hand, are harmful to organisms and tend to accumulate primarily due to environmental pollution sources (e.g., Pb, Hg, Cd). The pollution levels of metals (Al, Fe, Cd, Cr, Cu, Ni, Pb, Hg, Zn) and metalloid (As) in the sediments were assessed with Igeo several indices (Table 2).

Igeo, introduced by Karl H. Müller in 1969, measures metal pollution in sediments, allowing comparisons between current metal levels and self background levels (There are no specific limit values in our country). This widely used index helps monitor pollution trends and identify sources in areas, particularly those affected by industrial activity. The ecological risk level of metals in the sediment layer was determined using the PERI, developed by Hakanson (1980). PLI was a common method developed by Tomlinson et al.(1980) to assess the extent of the pollution status of toxic metals.

Sediment Quality Guidelines (SQGs) such as Effects Range Low (ERL), Effects Range Median (ERM), and Probable Effect Level (PEL), provide standards for assessing the ecological impacts of pollutants in sediments. ERL and ERM, developed by Long and Morgan (2000), reflect the probability of adverse effects, with ERL indicating minimal risk and ERM indicating moderate risk. The PEL, developed by the Canadian Council of Ministers of the Environment (CCME), indicates a high likelihood of adverse effects.

Table 2. Used Contamination indexes Igeo - (Müller, 1981), PLI - Tomlinson et al. (1980) and PERI - Hakanson (1980) formula and evaluation.

Index Name	Formulation	Evaluation
Igeo **C_n:** Measured concentration of the metal in the sediment (mg/kg) **B_n:** Geochemical background concentration of the metal (mg/kg) **1.5:** A constant for natural background variations and minor anthropogenic influences.	$I_{geo} = \left(\frac{C_n}{1.5R_n}\right)$	Uncontaminated [Igeo ≤ 0]
		Slightly contaminated [0 < Igeo < 1]
		Moderately contaminated [1 < Igeo < 2]
		Moderately Severe contaminated [2 < Igeo < 3]
		Severe contaminated [3 < Igeo < 4]
		Very Severe contaminated [4 < Igeo < 5]
		Extremely Severe Enrichment [5 < Igeo]
PLI **CFi:** Contamination Factor for each metal/element **n:** the number of analyzed metals/elements	$\sqrt[n]{(CF_1 * CF_2 * \ldots * CF_n)}$	Background concentration [PLI=0]
		Uncontaminated [0 < PLI ≤ 1]
		Slightly contaminated [1 < PLI ≤ 2]
		Moderately contaminated [2 < PLI ≤ 3]
		Severe contaminated [3 < PLI ≤ 4]
		Very Severe contaminated[4 < PLI ≤ 5]
		Extremely Severe Enrichment [PLI > 5]
PERI **E_r^n**: The monomial potential ecological risk factor **T_r^n**: The response coefficient for the toxicity of the single metal	$E_r^n = T_r^n * ({}^{C_n}/_{R_n})$	Low Risk [$E^i_r < 5$]
		Moderate Risk [$5 \leq E^i_r < 10$]
		Considerable Risk [$10 \leq E^i_r < 20$]
		High Risk [$20 \leq E^i_r < 40$]
		Very High Risk [$40 \leq E^i_r$]

Statistical Analysis: A statistical analysis of total organic carbon and heavy metal concentrations was performed. The statistical reliability of the data was evaluated by verifying normality and homogeneity by the Kolmogorov–Smirnov and Levene tests, respectively. The non-parametric Kruskal–Wallis test (K–W) was applied for variables that failed to satisfy the assumptions of normality and homogeneity. Spearman correlation analysis was employed to ascertain the degree and direction of possible relationships among variables. The statistical analysis was conducted using SPSS version 26.0.

RESULTS AND DISCUSSION

Grain size and organic carbon: Grain size and TOC analyses are important in sediment classification and determination of organic content to determine the general characteristics of the samples (Förstner & Wittmann, 1983; El-Said et al., 2014; Okay et al., 2016). Sediment samples from the stations studied in Izmir Bay predominantly consist of mud (< 63 µm; silt + clay) with an average percentage of approximately 73%. At stations 4, 7, 13, 17, 24, 26, 29, and 48, the highest grain size proportion is below 63 µm, whereas at stations 1 and 8, the highest grain size proportion ranges between 2 mm and 200 µm (Fig. 2). The results reveal that the fine mud fraction is dominant in some of the stations near the coastline and outer bay. The TOC value at station 24, located in the southern part of the inner bay and influenced by the Çiğli Wastewater Treatment Plant, was measured at the highest level. The lowest TOC values were observed at stations 1 and 8 located in the northwestern part of the bay. In the shallow zone of the study area, the sand ratio (> 63 µm) varies between 67.30-96.98%. While the TOC values in the deep stations (1, 4, 7, 8, 11,13,20) were low, the shallow stations under the influence of freshwater (17, 24, 26, 29, 48) had high TOC values. In addition, TOC contents were recorded as high in the southern inner, middle and outer parts of Izmir Bay.

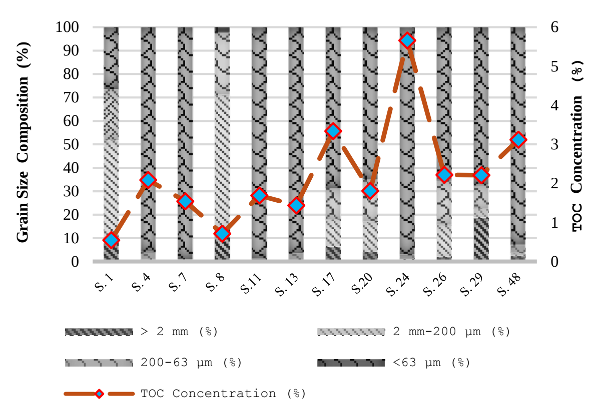

Figure 2. The spatial variations of grain size and TOC concentration in marine sediments of the inner Izmir Bay.

Evaluating the Metal Contamination Status: This study evaluated the metal results of sediment analyses and the TOC concentration in Izmir Bay using the ERL and ERM (Table 3). To assess metal pollution in Izmir Bay, the cumulative impacts on surface sediments and sediment quality were examined, detailing analytical results to illustrate the spatial distribution of total organic carbon (TOC) and seven metals (Cd, Cu, Cr, Ni, Pb, Zn, and Hg) and one metalloid (As) using ESRI ArcGIS Desktop 10.4 software.

The spatial distribution of metal content was visualized using the kriging interpolation method in ArcGIS (Fig. 3). Color classification was performed based on the minimum and maximum values of each metal. According to the distribution model, the northern part of Izmir Bay is highly contaminated with Zn, Hg, Cd, Cr, Hg, Cu and Pb (Fig. 3). concentrations are elevated in both parts of the inner Izmir Bay. The highest arsenic concentration was recorded at the southern entrance; however, the northern coast of Izmir Bay is more industrialized than the southern side. The shallow water sediments of the inner Izmir Bay are more contaminated due to discharge inputs, circulation patterns, and wave effects.

Table 3. The concentration levels of nine metals and metalloid (As) (mg kg^{-1}) and TOC (%) in the Izmir Bay sediments

Station Number	Depth (m)	Al	Fe	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	TOC
1	77	8930.99	12968.85	13.92	0.13	50.25	17.72	33.19	26.70	157.98	0.133	0.55
4	50	25476.34	40910.45	29.92	0.22	150.79	41.88	118.19	43.02	187.10	0.198	2.09
7	56	35741.34	40218.44	30.53	2.66	190.71	55.78	145.32	140.32	291.29	0.203	1.54
8	48	4318.38	7495.38	14.80	0.35	35.17	17.27	23.00	20.73	178.84	0.257	0.71
11	33	33943.76	45118.68	0.04	0.01	0.18	0.06	0.13	0.52	0.51	0.145	1.69
13	44	33830.30	44743.22	31.56	4.79	174.91	54.01	131.06	344.17	390.38	0.122	1.44
17	29	28349.52	2518864	21.53	2.91	131.59	43.07	83.98	133.21	291.47	0.175	3.34
20	51	30703.58	43269.60	0.03	0.00	0.17	0.04	0.12	0.05	0.23	0.129	1.81
24	14	29611.35	36874.07	24.05	0.50	173.83	75.73	101.96	65.55	381.05	0.264	5.66
26	23	22498.34	26733.60	16.72	0.14	91.77	30.45	59.75	38.55	247.96	0.093	2.23
29	4	31946.58	35654.69	37.86	3.25	339.95	83.40	160.03	169.91	352.69	0.238	2.22
48	26	49402.76	38587.55	22.05	0.19	166.36	52.56	121.56	48.85	317.10	0.140	3.13
Minimum	-	4318.38	7495.38	0.03	0.00	0.17	0.04	0.12	0.05	0.23	0.09	0.55
Maximum	-	49402.76	45118.68	37.86	4.79	339.95	83.40	160.03	344.17	390.38	0.26	5.66
Average	-	27896.11	33146.94	20.25	1.26	125.47	39.33	81.52	85.96	233.05	0.17	2.20
Standard Dev.	-	11961.63	12467.96	11.89	1.66	97.11	27.08	56.84	98.74	132.81	0.06	1.37
Shale Values[a]	-	92	47	10	0.3	100	50	80	20	90	0.3	NA
ERL[b]	-	NA	NA	8.2	1.2	81	34	20.9	46.7	150	0.15	NA
ERM[b]	-	NA	NA	70	9.6	370	270	51.6	218	410	0.71	NA
TEL[b]	-	NA	NA	7.2	0.68	52.3	18.7	15.9	30.2	124	NA	NA
PEL[b]	-	NA	NA	41.6	4.2	160.4	108.2	42.8	112	271	NA	NA

NA: Not Available. [a]Krauskopf (1979). [b]LongandMacDonald(1998).

Various industrial sectors, including textile, metal processing, automotive sub-industry, chemical, and food industries, operate in the organized industrial zones located in the provinces of Izmir and Manisa, near the Gediz River. Specifically, the Manisa Organized Industrial Zone and Kemalpaşa Organized Industrial Zone are located close to the Gediz River. Additionally, the agricultural industry (e.g., food processing plants) increases water usage and waste discharge. When untreated, these waters released into rivers, lakes, reservoirs, or seas can elevate metal levels to an extent that poses a threat to ecological balance. Metals such as Cd, Pb, Cu, Cr, Ni, Zn and Mn exist in trace amounts within aquatic environments. The natural levels and accumulation of these metals vary across organisms (Yarsan et al., 2000). Consequently, the metals used in this study on Izmir Bay were evaluated in terms of their individual, cumulative, and toxic effects.

Zn was found at significantly high concentrations, particularly in the inner bay and coastal stations, which may be attributed to domestic wastewater and atmospheric emissions. Zinc-based primers are also commonly used in ship surface coatings (Okay et al., 2008). The primary sources of Cu include domestic and industrial wastewater, atmospheric deposition, and surface runoff (Mulligan et al., 2001; Lin et al., 2013). The Cu concentration at station 7, fed by the Gediz River, and at stations 24 and 29, located at wastewater discharge points, remained at high levels. Cu concentrations ranged from 0.04 to 83.40 mg kg^{-1}. Similar to Zn, copper is essential for aquatic life, though it can be toxic at high levels (Saher and Siddiqui, 2016).

The highest Cr concentration, approximately 339.95 mg kg^{-1}, was recorded in the southeastern part of the inner Izmir Bay, where domestic wastewater is the primary source of Cr pollution. The distribution of Ni showed similarities to that of Cr, with concentrations varying between 0.17 and 339.95 mg kg^{-1}. Elevated levels of Ni may be of lithogenic origin due to the proximity to terrestrial zones with abundant igneous rocks along the coastline, which may be transported into the marine environment through weathering/erosion (Talas et al., 2023). Hg was mostly classified within the uncontaminated category; however, the high Hg concentration observed at station 8 may be due to the presence of inactive mining sites located 4 km southeast of the Karaburun Peninsula. The Hg concentration within the sea is thought to be a remnant from prior times, as Hg particles may have accumulated in the sediment from previous mining activities in the region (Talas et al., 2023).

In 1996, Kontas noted that during periods of heavy rainfall, Hg concentrations in Izmir Bay increased due to water and sediment materials transported from land into the bay via streams (Kontas, 2006). The lowest concentrations of As, Cd, Pb, Ni, and Hg in the marine sediments of the inner Izmir Bay were found to be below 0.15 mg kg^{-1} compared to other metals. Guven and Akıncı (2008) analyzed Cr, Cu, Pb, and Zn concentrations in seven sediment samples collected from the inner Izmir Bay, highlighting that metal pollution was more concentrated near industrial discharge areas and around the port. Due to the counterclockwise current in Izmir Bay, pollution tends to be directed toward the northern part of the bay, which is expected to exhibit higher contamination levels. Talas et al. (2023) identified the pollution ranking of metals and a metalloid in the inner Izmir Bay as Zn > Cr > Ni > Cu > Pb > As > Hg > Cd, and in the middle bay as Cr > Zn > Ni > Cu > Pb > As > Hg > Cd, based on studies conducted from 2014 to 2018. The average metal and metalloid concentrations in the sediments of Izmir Bay followed a decreasing order of Zn > Cr > Pb > Ni > Cu > As > Cd > Hg.

Pollutants in the bay were cumulatively assessed according to the Igeo, indicator (Fig. 4). Based on the Igeo index, stations 1 and 8 were classified as uncontaminated for all metal groups throughout the bay. Stations in the inner bay were classified as slightly contaminated and moderately severe contaminated for all metal groups. The middle bay posed no risk for any stations and was categorized as uncontaminated and slightly contaminated. Hg was classified as uncontaminated for all stations. For Cd and Pb metals, stations 11 and 13 were evaluated as severely and very severely contaminated.

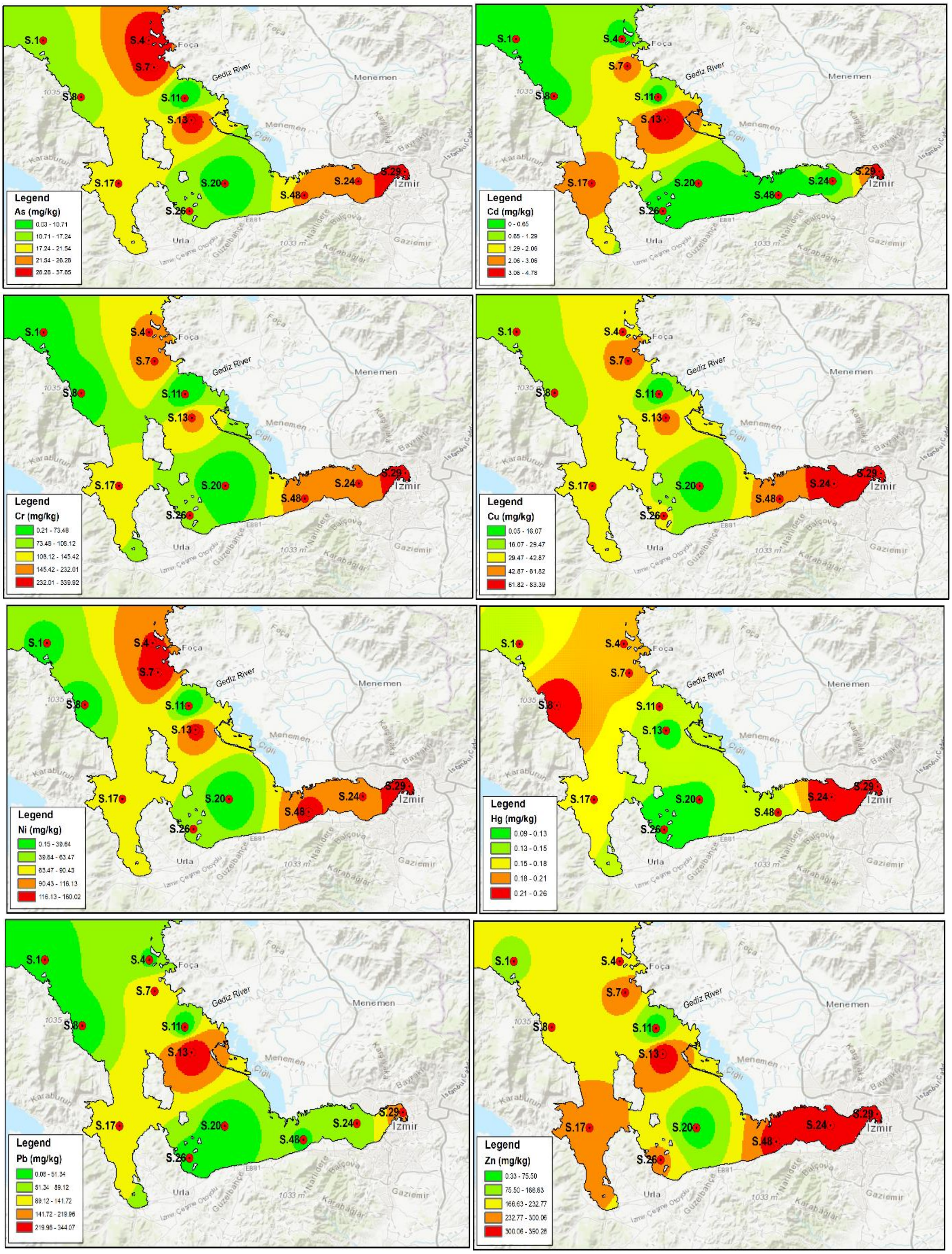

Figure 3. Spatial Distribution of Metals and Metalloid (As).

The pollutants are ranked according to the Igeo classification as Pb > Zn > As > Cd > Cr > Ni > Cu > Hg. According to the study by Talas et al. (2023), which includes data from 2014 to 2018, the pollutants in the inner and middle bay are ranked as Pb > Zn > Cr > As > Ni > Cu > Hg > Cd and Cr > As > Ni > Pb > Zn > Cu > Hg > Cd, respectively. Based on the SQGs (ERL–ERM), the most toxic metals are assessed as Ni, Pb, and Zn. In comparison, Cd and Hg exhibit lower toxicity levels. However, it was observed that Cd, Cr, and Cu have comparable toxicity levels at certain stations (Fig. 5).

Stations 7, 11, 13, 17, 24, and 29 as very high risk. In terms of the PLI index, stations 1, 8, and 26 were classified as uncontaminated; stations 4, 20, 24, and 48 as slightly contaminated; stations 7, 13, and 17 as moderately contaminated; and stations 11 and 29 as severely contaminated.

According to the PERI index, metals such as Zn, Cu, Ni, and Cr exhibit low to moderate risk levels across all stations, while Cd and As have higher risk levels compared to other metal types in the bay. In this study, pollutants are ranked according to the PERI classification as Cr < Zn < Cu < Ni < Hg < As < Pb < Cd, with the highest impact observed from the outer bay concentrations.

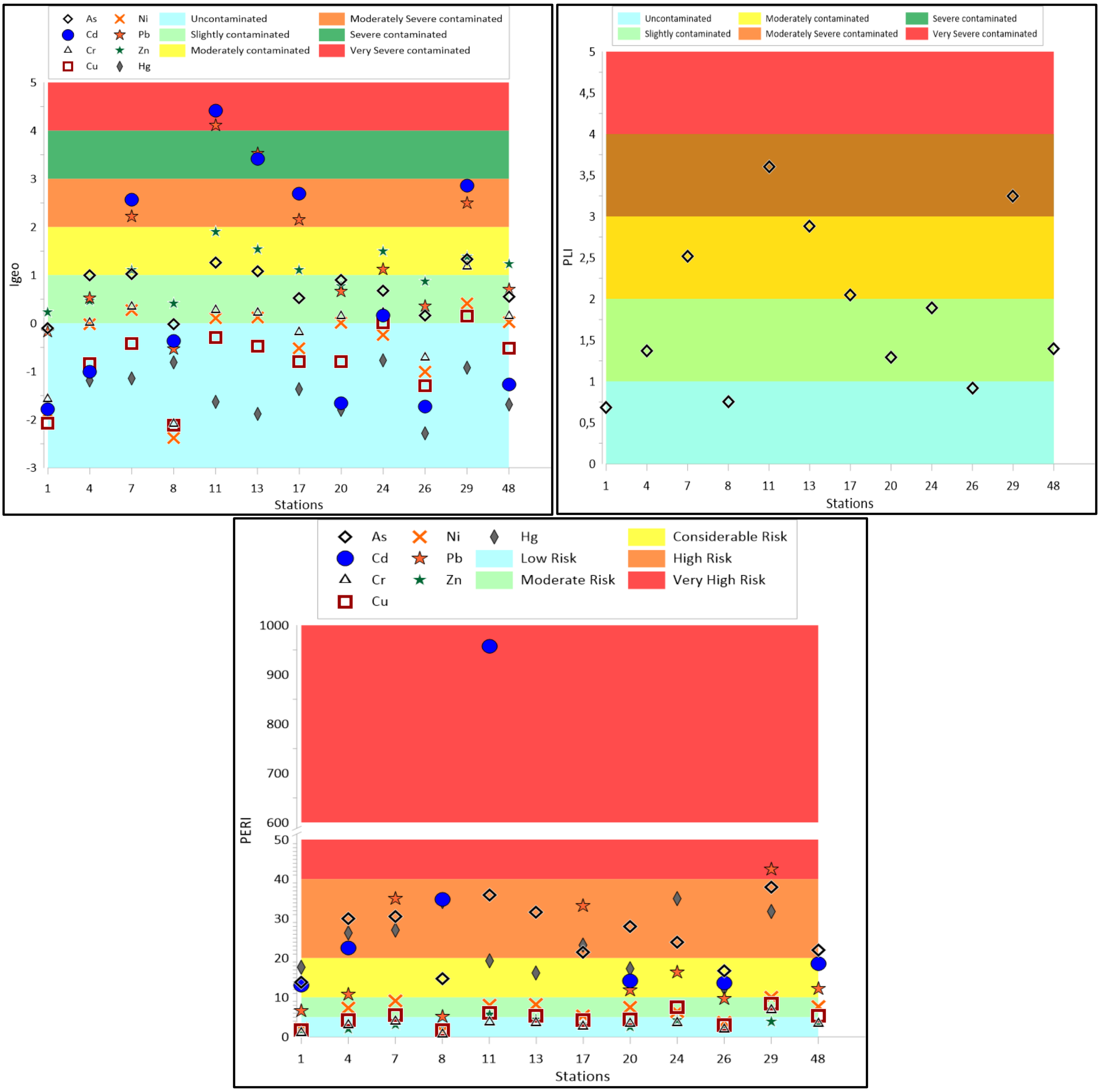

Figure 4. Igeo, PLI and PERI indices for the metals in the surface sediments of the Izmir Bay.

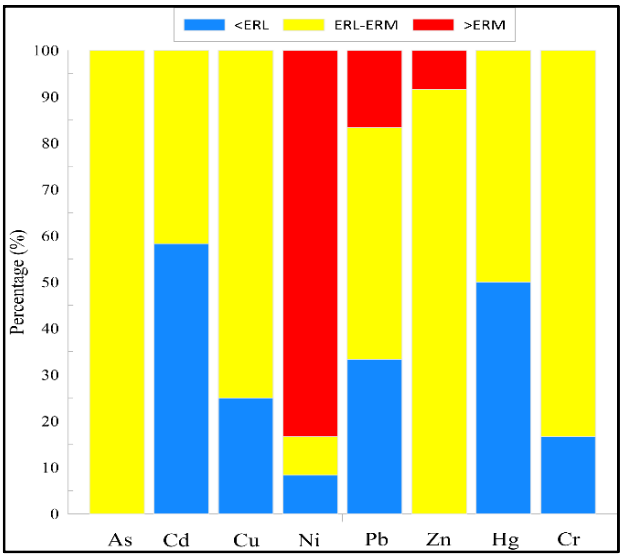

Figure 5. Assessment of the contamination (ERL–ERM) of the metals in the surface sediments of the Izmir Bay.

In stations 7, 11, 13, 17, and 29, extremely high pollution levels for cadmium and lead were observed compared to other sampled stations when assessed based on the Igeo indicator. It can be stated that the contribution of cadmium and lead to the overall pollution level is greater at these stations. The lead element originates from exhaust fumes of vehicles, waste from the petroleum industry, and paint waste. Cadmium, on the other hand, is one of the most toxic environmental pollutants, with even low concentrations having extremely harmful effects on aquatic organisms. One of the primary reasons for the accumulation of Cd in sediments is sewage sludge (Kara et al., 2018).

Station 17 showed higher average Cd values than the others. The primary reason for this is believed to be its proximity to fishing shelters, where chemicals used in repairs and painting are present. When pollutants are evaluated based on both individual and cumulative indices, it is evident that the concentrations at stations 11, 13, and 29 are higher compared to others. This is likely due to stations 11 and 13 being fed by the Gediz River and station 29's location near an area with intense port activities and wastewater treatment plant discharge.

According to Igeo values, light to moderate contamination of metals such as Cd and Pb has been detected at most sampling points. The quality criteria for metals indicate that nearly all sampling points have Cd, Pb, and Hg concentrations below ERL values. However, at most sampling points, Ni concentrations, as well as Pb and Zn concentrations at station 11, and Zn concentrations at station 13, significantly exceeded ERM values. As, Cr, Cu, and especially Ni and Zn concentrations pose a significant toxic risk to aquatic organisms according to sediment quality criteria (Güzel et al., 2022; Talas et al. 2023) concluded from their study using data from 2014 to 2018 that there is a high level of pollution in the inner bay and a low level in the middle bay. A comparison of the data in Table 4. clearly indicates that the sediments of the inner Izmir Bay are less polluted than those of Türkiye's coastal and bay regions and some estuaries worldwide..

Table 4. Sediment metal and metalloid concentrations of Izmir, Türkiye and other countries (mg kg^{-1} dry weight; minimum-maximum).

Location	Al(%)	Fe(%)	As	Cd	Cr	Cu	Ni	Pb	Zn	Hg	Reference
Izmir Bay	4318.38-49402.76	7495.38-45118.68	0.03-37.86	0-4.79	0.17-339.95	0.04-83.40	0.12-160.03	0.05-344.17	0.23-390.38	0.09-0.26	Present study
Izmir Bay	NA	12,40-76,899	NA	NA	NA	4.26-45.2	14.9-127	NA	25.6-154	NA	Kontas (2008)
Izmir Bay	NA	NA	NA	0.005-0.33	29-199	NA	NA	14-90	NA	0.05-0.99	Kuçuksezgin et al. (2006)
Karaburun Eagen Sea	29621	15,943	2.014	0.139	144	11.02	56.59	12.17	40.5	9.70	Ozkan et al. (2017)
Izmir Inner Bay	NA	32,500	23.07	0.45	114.28	64.49	86.64	79.36	219.00	0.51	Ozkan et al.(2022)
Akköy Bay	NA	23,362-29,939	NA	0.13-0.19	156-230	16.2-20.9	172-235	17.5-19.7	54.5-68.8	0.055-0.076	Kuçuksezgin et al. (2022)
Güllük Bay	NA	10,791-13,740	NA	0.13-0.20	31.7-36.1	7.90-13.7	31.1-37.0	15.2-17.6	32.5-54.6	0.025-0.033	Kuçuksezgin et al. (2022)
Edremit Bay	1.8-8.17	1.24-4.86	12-63	NA	26-200	6.4-51.5	14.6-136.9	16.8-63.7	31-123	NA	Duman et al .(2022)
Izmit Bay of the MS	NA	2.78–5.89	4-11	0.10-1	41-121	50-105	19-73	10-34	124-363	0.05-1	Tan & Aslan (2020)
Erdek Bay of the MS	1.1-9.2	0.8-4.6	NA	NA	11-238	3-52	8-149	19-61	34-272	0.04-3.10	Balkıs & Çağatay (2001)
Marmara Sea (MS)	1.1-11	0.6-7.7	NA	NA	11-654	3-107	8-1731	10--85	33-410	0.04-3.0	Algan et al. (2004)
Nemrut Bay of the Aegean Sea	NA	1.05-4.58	NA	0.005-0.25	35.7-98.8	9.6-43.7	18.1-63.4	22.3-89.4	75-271	1.70-9.60	Esen et al. (2010)
Aliağa Bay of the Aegean Sea	NA	3.23-5.46	NA	0.06-3.94	65-264	20-703	28-240	91.3-751	86-970	0.32-7.02	Neşer et al. (2012)
Coastal Bohai Bay, China	NA	NA	NA	0.12-0.66	601-224.5	20.1-62.9	23.4-52.7	20.9-66.4	55.3-457.3	NA	Gao & Chen (2012)
Algericas Bay, Spain	NA	3.05	NA	11.05	NA	15	81.5	25.5	75	NA	Diaz-de Alba et al. (2011)
Al-Khobar, Arabian Gulf	NA	0.75	NA	0.226	NA	182.97	75.1	5.358	52.68	NA	Alharbi & El-Sorogy (2017)
Lima Estuary, Portugal	NA	NA	NA	NA	39-110	71-531	18-34	86-89	183-1133	NA	Cardosa et al. (2008)
Montevideo Harbor, Uruguay	NA	NA	NA	NA	79-253	59-13	26-34	44-128	174-491	NA	Muniz et al. (2004)

The investigated stations exhibited distinct contamination and risk profiles. According to the Igeo results, most stations were classified as uncontaminated or slightly contaminated, although Cd and Pb frequently reached higher contamination levels. In particular, moderately to very severe contaminated conditions were detected for Cd and Pb at some stations, indicating localized accumulation. The PLI values identified stations 11 and 48 as Severe contaminated, while station 29 was classified as moderately contaminated. These findings highlight that pollution pressure is more intense at these locations. The PERI assessment revealed that ecological risks were mainly associated with Cd, Pb, As, and Hg.

Station 1 was mostly uncontaminated with respect to Igeo and classified as uncontaminated by PLI; however, it showed considerable risk due to Cd, As, and Hg in the PERI evaluation. At station 4, contamination remained Slightly contaminated, but Cd, Hg, and As resulted in High Risk. Stations 7 and 17 showed Moderately severe contamination of Cd and Pb, with PERI indicating considerable to high risk primarily due to Pb, As, and Hg. Although station 8 was classified as Uncontaminated in terms of PLI, the PERI results revealed High Risk from Cd and Hg.

Station 11 emerged as one of the most critical sites, with Cd and Pb reaching Very Severe contamination and PERI indicating Very High Risk for Cd. Similarly, at station 13, Cd and Pb showed moderately severe to Severe contamination, while As and Hg dominated the high risk category in PERI. Stations 20, 24, and 26 were mostly uncontaminated or slightly contaminated in Igeo and PLI, but As and Hg contributed to considerable to high risk in PERI.

Finally, stations 29 and 48 were identified as high-priority sites. PLI classified both as severe contaminated, and PERI results showed that Pb posed very high Risk at station 29, while As was the main driver of high risk at station 48. These findings indicate that Cd and Pb are the dominant contaminants shaping pollution levels, whereas Hg and As play a crucial role in ecological risk assessments.

The correlation coefficients in Table 5 demonstrate the directions and strengths of the relationships between TOC parameters and heavy metal concentrations. There is no relationship between Hg and any metal. A weak positive correlation is shown by TOC, Cu and Zn. A strong positive correlation was found to exist between As, Cr, Cu, Ni, and Pb (Table 5). These metals are commonly associated with activities such as the manufacturing of chemical fertilisers and nitrogen compounds, manufacturing of iron and steel products and ferroalloys, copper production, and operations in urban wastewater.

Tablo 5. Spearman's rank correlation matrix for heavy metal concentrations and TOC parameters.

	As	*Cd*	*Cr*	*Cu*	*Ni*	*Pb*	*Zn*	*Hg*	*TOC*	
As	**1.000**									**1**
Cd	0.853	**1.000**								**0.8**
Cr	0.965	0.811	**1.000**							**0.6**
Cu	0.909	0.804	0.972	**1.000**						**0.4**
Ni	0.965	0.776	0.979	0.916	**1.000**					**0**
Pb	0.923	0.916	0.937	0.916	0.916	**1.000**				**-0.4**
Zn	0.832	0.832	0.86	0.902	0.804	0.902	**1.000**			**-0.6**
Hg	0.322	0.385	0.329	0.413	0.252	0.196	0.210	**1.000**		**-0.8**
TOC	0.2	0.140	0.259	0.406	0.210	0.245	0.441	0.175	**1.000**	**-1.0**

CONCLUSION

This study provides a comprehensive evaluation of the spatial distribution, contamination levels, and ecological risks of metals and metalloids in the surface sediments of Izmir Bay. The findings indicate that the inner and northern parts of the bay experience higher metal contamination, primarily due to anthropogenic activities such as industrial discharges, domestic wastewater inputs, port operations, and riverine transport of pollutants, particularly from the Gediz River. In contrast, stations in the outer and middle bay generally show lower contamination levels, reflecting the reduced impact of direct human activities. The analysis of sediment grain size and TOC content confirmed that fine-grained sediments with higher organic matter act as significant sinks for metal accumulation. Strong correlations between TOC and metals including Cu, Zn, Cr, and Pb suggest that organic matter plays a key role in metal binding and retention, whereas the weak correlation of Hg with other metals implies that its occurrence may be driven by localized inputs, such as historical mining activities or sediment remobilization.

Assessment based on the Igeo classified most stations as uncontaminated to slightly contaminated; however, localized hotspots, particularly for Cd and Pb, were identified. PLI and PERI further highlighted that several stations, including 11, 13, 17, 29, and 48, exhibited severe contamination or very high ecological risks. Cd and Pb emerged as the dominant pollutants contributing to both contamination and ecological risk, while As and Hg played an important role at specific stations. Comparison with SQGs revealed that Ni, Pb, and Zn frequently exceeded threshold values, indicating a high potential for toxic effects on benthic organisms and the broader aquatic ecosystem. Spatial analysis confirmed that the inner and northern parts of the bay, where industrial and domestic activities are concentrated, represent the most critical zones in terms of pollution management and ecological risk.

Overall, the study underscores the importance of continuous monitoring of sediment quality in Izmir Bay, particularly in areas with intense anthropogenic pressure. The results provide a scientific basis for identifying priority areas for mitigation, including port regions, wastewater discharge points, and river inflow zones. Management strategies should focus on reducing Cd and Pb inputs, improving the efficiency of wastewater treatment plants, and implementing stricter controls on industrial discharges. Furthermore, dredging and port activities should be carefully managed to prevent remobilization of contaminated sediments, while environmentally friendly technologies, cleaner production practices, and regular sediment monitoring programs should be promoted to minimize pollution sources. Sampling conducted in May 2021, during the COVID-19 pandemic, showed lower concentrations of certain metals, particularly Pb, compared to previous studies, suggesting that pollutants from coastal areas, in addition to shipping and port activities, significantly affect the Bay. It is recommended that future studies include additional sampling stations to more accurately capture spatial variability.

In conclusion, Izmir Bay is a highly dynamic system influenced by both natural and anthropogenic processes. While some areas of the bay exhibit low contamination levels, localized hotspots present elevated ecological risks, highlighting the need for targeted and sustained management interventions. This study not only provides essential baseline data for assessing sediment quality but also contributes to the development of long-term strategies for pollution mitigation and ecosystem protection in Izmir Bay.

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