# SPATIOTEMPORAL MODELLING OF HEAVY METAL POLLUTION AND WATER QUALITY DEGRADATION IN KARACHI'S COASTAL WATERS: THREAT TO MARITIME SUSTAINABILITY

**Muhammad Irfan[1], Bassam Nasir[2], Rabia Arif[1*], Shaista Mahmud[1], Mohammad Idrees[3]**

[1] Department of Earth & Environmental Science, Bahria University Karachi Campus, Pakistan
Email: mirfan.bukc@bahria.edu.pk; shaistaiftikhar.bukc@bahria.edu.pk; rabiaarif339627@gmail.com
[2] Department of Civil, Construction and Environmental Engineering, University of Central Florida, USA
Email: bnasir@ucf.edu
[3] Bahria School of Maritime and Applied Sciences, Bahria University Karachi Campus, Pakistan
Email: muhammadidrees.bukc@bahria.edu.pk

***Abstract***

*The industrialization, maritime operations, and urban expansion adjacent to major port cities around the world are becoming a threat to coastal ecosystems. The research presents a decade review on spatiotemporal analysis of water quality along a Karachi coastal zone, one of Pakistan's most active maritime and economic sectors. Physico-Chemical parameters and Heavy metals were evaluated to quantify the Water Quality Index (WQI), correlation analysis, Heavy Metal Pollution Index (HPI), and statistical analysis. The major parameters were pH, Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Chromium (Cr), Nickel (Ni), Cadmium (Cd), Arsenic (As) and Lead (Pb) were gathered for six different locations i.e. Sandspit, Hawksbay, Seaview, Manora, Gizri Creek and mouth of Lyari River. The modeling trend revealed a severe degradation in water quality at Seaview and Gizri Creek due to untreated sewage, industrial effluent, shipping operation discharges, and port activities. The research summarizes a strong correlation between metallic and organic pollutants due to maritime transport, the absence of wastewater treatment, and unsustainable ship-breaking practices. The Manora Beach water quality is comparatively stable due to isolation from the direct influence of pollutants. The sustainability of the coastal zone was also measured to predict the future risk by projecting the WQI for 2030. The forecast shows that maximum deterioration at Sea view exceeds the critical threshold and greatly influences the coastal tourism, marine biodiversity and aquatic life. The integrated analysis provides a comprehensive dataset and establishes a baseline for environmental monitoring for coastal zone management. The results highlight the vulnerable zone to adopt the mitigation plans and sustainable development strategies for Pakistan's coastal and maritime economic corridors.*

***Keywords***: *coastal water quality, Karachi, maritime industry, heavy metals, pollution trend, urbanization.*

## 1. Introduction

Sustainable coastal ecosystems are very important socio-economic zones to support the diverse marine life and livelihoods[1]. The coastal ecosystems also play an important role in

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promoting green maritime trade and transit[2]. However, human activity is continually threatening these ecosystems, particularly in densely populated cities along the coast[3]. The research highlights that one of the largest developing maritime and economic hubs, Karachi, Pakistan, supports a diverse range of activities, such as commercial shipping, naval operations, fishing, port-based businesses, industries, and rapidly expanding coastal urban populations[4] (Figure 1). The region is facing a substantial increase in marine pollution, leading to ecological degradation and loss of biodiversity[5].

The International Maritime Organization (IMO) and other international environmental authorities around the world have emphasized the critical need to monitor and manage pollution from maritime sources such as ballast water discharge, port runoff, ship-breaking activities, and untreated industrial effluents[6]. The Karachi coastal zone is an important part of the South Asian Coastline[7]. It is the backbone of Pakistan's Blue Economy goal and provides the linkage between the China-Pakistan Economic Corridor (CPEC) and the regional maritime sector[8]. The environmental monitoring of coastal water quality needs continuous evaluation and data collection for integrated studies to address the pollution from different sources[9].

Earlier research has investigated pollution at different locations for chemical oxygen demand (COD), biological oxygen demand (BOD), and hazardous heavy metals like chromium (Cr), lead (Pb), and cadmium (Cd)[10]. The fragmented structure of this research provides point-based water pollution and is unable to build a regional contamination baseline. The effective environmental governance, policy implementation, and compliance with IMO protocols (MARPOL Annex V: regulates the waste discharges and maritime pollution from ships) play a key role in controlling coastal water pollution[11].

The current study was conducted to bridge the knowledge gap through a spatio-temporal meta-analysis of the published water quality data. The published data from 2010–2021, for six sites in Karachi coastal areas, namely, Seaview, Hawksbay, Sandspit, Manora Beach, Gizri Creek

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[6] Leary, D. (2023). International Maritime Organization (IMO). Yearbook of International Environmental Law, 34(1), yvae024.
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[8] Butt, H. D., Aijaz, M. U., Shamim, M. A., Lodhi, K. S., Hayat, A., & Mazhar, M. (2024). Leveraging CPEC for a thriving blue economy and coastal development. Migration Letters, 21(S8), 1285-1321.
[9] Majeed, R., Fatima, S. U., Khan, M. A., Khan, M. A., & Shaukat, S. S. (2021). Spatio-temporal analysis of pollutants in Karachi coastal water. EQA-International Journal of Environmental Quality, 42, 6-21.
[10] Memon, A. G., Mustafa, A., Raheem, A., Ahmad, J., & Giwa, A. S. (2021). Impact of effluent discharge on recreational beach water quality: a case study of Karachi-Pakistan. Journal of Coastal Conservation, 25(3), 37.
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and Lyari River outfall, have been analyzed. These sites were chosen strategically due to their proximity to high-impact maritime activities such as port terminals, naval stations, recreational beaches, and outfall zones. The major Physiochemical and heavy metal characteristics were retrieved, standardized, and statistically evaluated to determine regional patterns, pollution sources, and temporal variations. Water Quality Index (WQI) and linear regression models were used to forecast water quality trends through the year 2030. Gizri Creek and the Seaview are highly vulnerable to pollution and associated persistent degradation, which are not only threatening the already fragile ecosystem but also posing a great threat to human health, aquaculture, marine operations and coastal tourism. This research focuses on providing insights for building a framework by marine regulators, urban planners and the port authorities for marine environmental protection. This research aligned with the UN SDG 14 (life below water) and supports the development of evidence-based environmental monitoring.

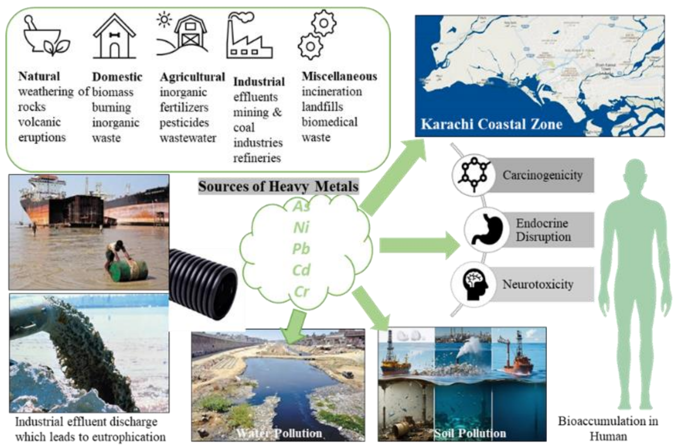


Figure 1. Sources of Heavy metal pollution in Karachi coastal zone

## 2. Literature Review

The marine ecosystem has an adverse impact on economic activities and public health in coastal regions due to continuous degradation. Primarily, coastal water pollution from urban and industrial settings has received considerable global attention. The continuous flow of domestic sewerage, industrial effluents, maritime transport is highly vulnerable to coastal zones[12]. Despite the presence of legal obligations to reduce the maritime pollution from ships, oil discharges, sewage, and garbage under the International Frameworks, such as the International Maritime Organization (IMO), MARPOL Convention (Annexes I, IV, and V), monitoring and enforcement are still inconsistent in the developing coastal cities[13]. The studies conducted along Karachi's coastal belts have documented severe water pollution. The identified alarming concentration of heavy metals such as Cadmium (Cd), Chromium (Cr), Lead (Pb) and Nickel (NIi) near port and

[12] Rangel-Buitrago, N., Galgani, F., & Neal, W. J. (2024). Addressing the global challenge of coastal sewage pollution. Marine Pollution Bulletin, 201, 116232. https://doi.org/https://doi.org/10.1016/j.marpolbul.2024.116232
[13] IMO. (2021). Articles, Protocols, Annexes, Unified Interpretations of the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex IV & V.

shipbreaking yards[14]. Heavy metal accumulation in the channel is contributed to by ship-related operations. Most of these studies, however, have limited utility for long–term policy formulation or environmental risk assessment due to a lack of temporal depth or spatial comparison. Furthermore, these studies do not apply composite indices such as the Water Quality Index (WQI) and Heavy Metal Pollution Index (HPI).

The integrated coastal water quality monitoring with Sustainable Development Goal 14 (Life Below Water) has been adopted by countries to establish comprehensive frameworks for marine ecosystem conservation. The UN Decade of Ocean Science (2021-2030) highlights the need for integrated observation systems and data harmonization in establishing sustainable ocean governance[15]. The standardized monitoring tools, such as the European Union's Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD), have been implemented by advanced economies. Both tools incorporate WQI-based assessments, heavy metal thresholds, and predictive models to forecast ecological degradation. However, the similar systems in Pakistan are still underdeveloped due to the lack of baseline data consolidation and forecasting trends are rarely undertaken.

In 2017, the IMO's Ballast Water Management Convention (BWMC) was implemented with a mandate of the treatment of ballast water to reduce invasive species and chemical contamination. Despite this, at Karachi port, the monitoring remains limited. The unified long-term datasets, comparative site assessments, and predictive modeling do not exist for the Karachi coastal zone. Previous research was conducted to identify the heavy metal concentration in seawater and sediment. The elevated concentration was observed mainly for Cadmium, Lead and Chromium due to industrial effluents, ship waste and urban sewage[16]. The studies also reported higher levels of BOD and COD due to organic pollution and depletion of oxygen near outflow water bodies. The quantification of the temporal dynamics of pollution levels using meta-analytical techniques and the linked findings with future risks to maritime sectors such as fisheries, aquaculture, and port logistics has been done in a few studies only. The formulation of effective mitigation strategies, compliance with the absence of harmonized water quality indicators with international maritime environmental standards, and the design of Early Warning Systems (EWS) are hindered due to the lack of harmonized water quality indicators for different locations. The data of land-based pollution sources (river input from Lyari and Malir) is not integrated in marine pollution forecasting framework.

## 3. Materials and Methods

The research was carried out to evaluate the water quality on six main coastal sites (Sandspit, Hawksbay, Seaview, Manora, Gizri Creek and the mouth of the Lyari River) in Karachi,

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[15] Hatje, V., Rayfuse, R., Polejack, P., Goddard, C., Jiang, C., Jones, D., Faloutsos, D., Fiedler, H., Akrofi, J., Sheps, K., Leung, K., Pinheiro, L. M., Pradhan, M., Castrillejo, M., Bustamante, P., Kershaw, P., Zitoun, R., Silva, S., & Kiefer, T. (2024). Ocean Decade Vision 2030 White Papers – Challenge 1: Understand And Beat Marine Pollution [Research Report](doi:10.25607/6m86-s908). (The Ocean Decade Series, Issue. https://oceanrep.geomar.de/id/eprint/61239/

[16] Qari, R., & Siddiqui, S. A. (2008). Heavy metal pollution in coastal seawater of Nathia Gali, Karachi (Pakistan). Journal of Environmental Research and development, 3(1), 9-19.

Pakistan (Figure 2). These sites are directly exposed to various human-induced pollution such as urban sprawl, industrial discharge, port activities and sewage outfalls. Data was acquired from last 10 years (2010-2021) peer reviewed publication and government report that include physiochemical and heavy metals[17,18,19,20,21,22,23,24,2526]. This secondary data comprises in-situ measurement of pH and salinity using a portable instrument. The consistency and reliability of data were ensured by compiling Scopus/Web of Science and government reports. The water samples were collected from the surface (0-1m depth) using pre-cleaned one-liter polyethylene bottles, ensuring no contamination. Samples were taken from both high and low tides to estimate the average and capture the full range of variability in pollutant concentrations across tidal cycles. Standard sampling procedures were followed to prevent any cross-contamination, and all bottles were acid-washed and rinsed with deionized water before use[27]. The sample was preserved by adding concentrated $HNO_3$, which helps to prevent metal ions from adhering to the container walls. Finally, sample was transported to the laboratory within 24 hours to maintain the integrity of the samples. Chemical parameters were measured by HACH, such as Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The presence of heavy metals (Cd, Cr, Ni, As, Hg, and Pb) was determined by using an Atomic Absorption Spectrophotometer (AAS) and Inductively Coupled Plasma–Mass Spectrometry (ICP-MS).

Initially, data was processed to standardize the unit of salinity converted to parts per thousand (ppt), BOD and COD into mg/L. The data consistency was evaluated by using linear interpolation. The compiled data was utilized to estimate the statistical analysis (mean, minimum, max and standard deviation) for each site to evaluate the temporal changes and anomalies.

[17] Ayaz, M., & Khan, N.-U. (2019). Forecasting of heavy metal contamination in coastal sea surface waters of the karachi harbour area by neural network approach. Nature Environment and Pollution Technology, 18(3), 719-733.

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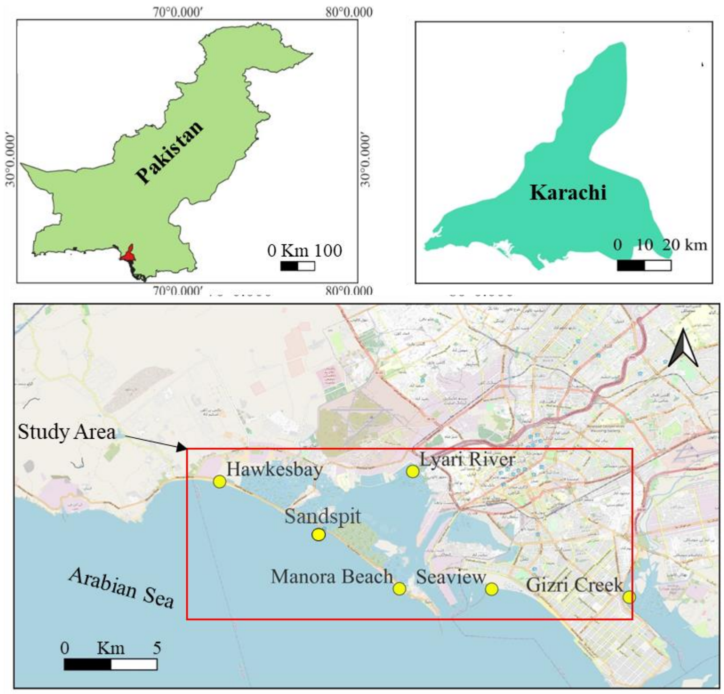


Figure 2. Location map of the study area, Karachi, Pakistan

The water quality index (WQI) was calculated by using the estimated mean value of physiochemical parameters in order to present a single metric (equation 1)[28]. The quality rating (Qi) was calculated for each i[th] water quality parameter using equation 2.

$$\mathrm{WQI} = \frac{\sum_{i=1}^{n}(\mathrm{Qi.Wi})}{\sum_{i=1}^{n}\mathrm{Wi}} \qquad (1)$$

Where ∑ the sum of all parameters and n is the total of water quality parameters considered in the study.

$$Q_{i=}\frac{C_i - C_{ideal}}{S_i - C_{ideal}} \times 100 \qquad (2)$$

$C_i$ is the measured value of the [ith] parameter in the water sample, $C_{ideal}$ is the present ideal value of the i[th] parameter and Si for standard permissible value of the i[th] parameter as per the standard.

[28] Patel, P. S., Pandya, D. M., & Shah, M. (2023). A systematic and comparative study of Water Quality Index (WQI) for groundwater quality analysis and assessment. Environmental Science and Pollution Research, 30(19), 54303-54323.

Table 1. Standard Range of Water Quality Index (WQI) to define water quality rank[29].

| WQI Range | Water Quality Rank |
|---|---|
| 0–50 | Excellent |
| 51–100 | Good |
| 101–200 | Poor |
| 201–300 | Very Poor |
| >300 | Unsuitable for Use |

WQI temporal variation and individual water quality parameters were visualized by time series plots. The spatial variation between stations was analyzed using heat maps and boxplots. The water quality trend forecast was estimated by applying a linear regression model from 2022 to 2030 to identify the critical zones (equation 3).

$$WQI_t = \beta_0 + \beta_1 t + \varepsilon \quad (3)$$

Where WQI is water quality, t is year, $\beta_0$ is WQI at time zero or baseline level, $\beta_1$cofficient of slope or trend (indicate rate of change in WQI, t time in years and ε error term.

The heavy metals for selected sites were also analyzed for Cr, Ni, Cd, As, and Pb. The summarized values were compared with marine water quality standards[30] to evaluate the pollution index (Figure 3a). Pearson's correlation coefficients were applied to observe the relationships among heavy metals and organic pollutants (BOD, COD), which represent shared pollution sources[31]. The Heavy Metal Pollution Index (HPI) was estimated to use equation 4[32] and compared with the standard HPI classification (Figure 3b).

$$HPI = \frac{\sum_{i=1}^{n}(Qi.Wi)}{\sum_{i=1}^{n} Wi} \quad (4)$$

Where $W_i$ is the weight of the $i^{th}$ metal and is inversely proportional to the standard permissible limit of metal (µg/L).

$Q_i$ is estimated by $(\frac{(C_i-I_i)}{S_i-I_i}) \times 100$, where $C_i$ is the measured concentration of the $i^{th}$ metal, and $I_i$ is the ideal concentration of the $i^{th}$ metal.

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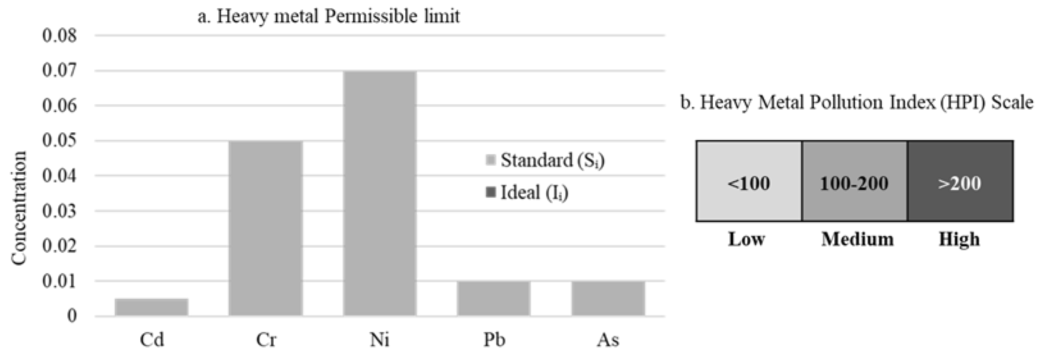


Figure 3 a. Heavy metal permissible limit in µg/L b. Heavy Metal Pollution Index (HPI) classification.

HPI trends were graphed over time for each site. Spatial variability was mapped to identify heavy metal pollution hotspots. The forecast has been calculated to predict the metal pollution index ($HPI_t$) for 2022-2030 using the linear regression model equation 5.

$$HPI_t = \alpha_0 + \alpha_1 t + \varepsilon \qquad (5)$$

Where HPI, heavy metal pollution index and t for year, $\alpha_0$ baseline HPI value, $\alpha_1$ HPI rate of change and ε error account for random variation

The outcomes were compared with the national and international standards. The guidelines for marine water, regulation defined by the International Maritime Organization (IMO), particularly MARPOL Annex IV & V, and the Pak EPA. Finally, the data was analyzed using R/Python for statistical analysis and graphical presentation, and GIS for pollution spatial mapping.

## 4. Results & Discussion

### 4.1 Physico-Chemical Water Quality Analysis

The pH value defined the acidity and alkalinity of water samples, ranging between 7.3-7.5, which shows a neutral to slightly alkaline nature. The acceptable range of pH ranges from 6.5 to 8.5 for aquatic life in coastal zones. The results show that 7.3 is the lowest observed value compared to the remaining sites. The DO ranges from 1.4-3.42 mg/L. The minimum value at Manora and the maximum DO were found at Seaview. The optimum value is ≥5 mg/L for healthy aquatic ecosystems. Hawksbay and Manora represent low DO levels due to higher pollution and decrease the oxygen for marine organisms. Seaview and Lyari outfall DO level is fair due to aeration and tidal influence (Figure 4a).

The salinity ranges from 22.9-28.9 (Figure 4b). The observed ranges show minimum at Manora and maximum for Gizri Creek. The high value of salinity at Gizri and Hawksbay reflects the restricted freshwater and evaporation. The lower value at Manora is due to mixing of freshwater intrusion and sewage dilution. COD higher value observed on selected stations range from 377.3-757.6 mg/L. The maximum COD observed at Seaview shows significant chemical pollution and the presence of oxidizable pollutants. COD reflects the organic and industrial pollution at Seaview, Gizri and Hawksbay.

BOD elevated level ranges from 172.2 mg/L at Manora beach and 279.6 mg/L at Gizri Creek. The values are greater than the permissible limit, i.e., ≤ 3-6 mg/L. These values highlight extensive microbial activity and organic contamination, possibly from untreated industrial effluents and domestic sewage. Hawksbay and Gizri Creek marine biodiversity are at high risk due to oxygen reduction.

The physicochemical results revealed that high BOD & COD in correlation with DO level at selected stations are facing organic and chemical contamination. Seaview, Hawksbay and Gizri Creek are highly polluted, possibly due to industrial effluence, domestic discharge and port operations. COD and DO are lower at Lyari and Manora but exceed the threshold values.

Table 2 Average Physio-chemical parameter values (2010–2021)

| Site | pH | DO (mg/L) | Salinity (ppt) | COD (mg/L) | BOD (mg/L) |
|---|---|---|---|---|---|
| Seaview | 7.47 | 3.42 | 26.69 | 757.65 | 201.85 |
| Hawksbay | 7.38 | 1.86 | 28.88 | 752.95 | 228.58 |
| Sandspit Beach | 7.38 | 2.02 | 25.61 | 650.52 | 223.89 |
| Gizri Creek | 7.45 | 3.07 | 28.92 | 722.55 | 279.61 |
| Manora Beach | 7.31 | 1.43 | 22.99 | 377.36 | 172.20 |
| Lyari Outfall | 7.45 | 3.18 | 26.43 | 442.90 | 196.68 |

WQI estimation exposed the severe pollution index across the Karachi coastal zone. Seaview, Sandspit, Hawksbay and Lyari were classified as Poor. The WQI value ranges from 111.7-187.3 (Table 3). The worst quality of water is at Gizri Creek where WQI is 207.9. Manora site is classified as Good with WQI 92.8 relatively better quality. The WQI trend shows extensive pollution near urban and industrial points.

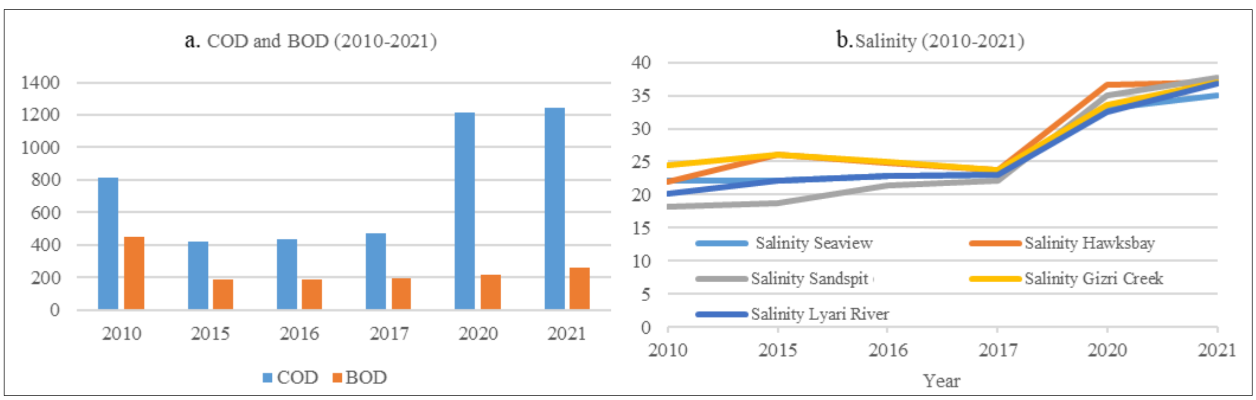


Figure 4. Physiochemical parameter (2010-2021) a. COD & BOD, b. Salinity.

Table 3. Water Quality Index (WQI) summary for six stations, Karachi Coastal Zone.

| Site | Mean WQI | Water Quality Category |
|---|---|---|
| Seaview | 179.5 | Poor |
| Hawksbay | 187.3 | Poor |

| | | |
|---|---|---|
| Sandspit Beach | 163.4 | Poor |
| Gizri Creek | 207.9 | Very Poor |
| Manora Beach | 92.8 | Good |
| Lyari Outfall | 111.7 | Poor |

**4.2 Heavy Metal Pollutant Analysis**

The examination of six heavy metals i.e., Chromium (Cr), Cadmium (Cd), Nickel (Ni), Arsenic (As) and Lead (Pb) in the coastal water of Karachi. The estimated concentrations are higher than the permissible limits defined by Pak-EPA (2016) thresholds (Table 4). The Cd range from 0.06–0.75 µg/L exceeds the Pak-EPA limit of 0.01 µg/L**.** The Cr range from 0.05–0.63 µg/L exceeds the Pak-EPA limit of 0.05 µg/L. Ni range from 5.8–7.3 µg/L, whereas the limit is 0.02 µg/L[33]. Pb represents the range from 1.80–3.10 µg/L and as 0.05–0.75 µg/L; both metals are higher than the permissible limit i.e., 0.05 µg/L. Seaview and Gizri Creek are highly contaminated due to industrial discharge and untreated sewage. These metal concentrations are also violating the IMO MARPOL Annex V discharge protocols and threaten aquatic food chains, marine biodiversity and human health. The outcomes show an urgent need for pollution control, regulatory enforcement and regular monitoring to protect ecosystems under SDG 14 (Life Below Water). Figure 5 below represents the distribution of heavy metals in the study area.

Table 4. The estimated heavy metals in µg/L summary and comparison with the Pak-EPA limit.

| Site | Cd | Cr | Ni | Pb | As |
|---|---|---|---|---|---|
| Seaview | 0.75 | 0.63 | 6.70 | 3.10 | 0.75 |
| Hawksbay | 0.11 | 0.10 | 6.00 | 2.60 | 0.30 |
| Sandspit | 0.06 | 0.06 | 5.80 | 1.80 | 0.30 |
| Gizri Creek | 0.14 | 0.11 | 7.30 | 3.10 | 0.08 |
| Manora Beach | 0.06 | 0.05 | 6.00 | 2.00 | 0.05 |
| Lyari Outfall | 0.08 | 0.06 | 6.20 | 2.50 | 0.05 |
| PAK-EPA Limit | 0.01 | 0.05 | 0.02 | 0.05 | 0.05 |

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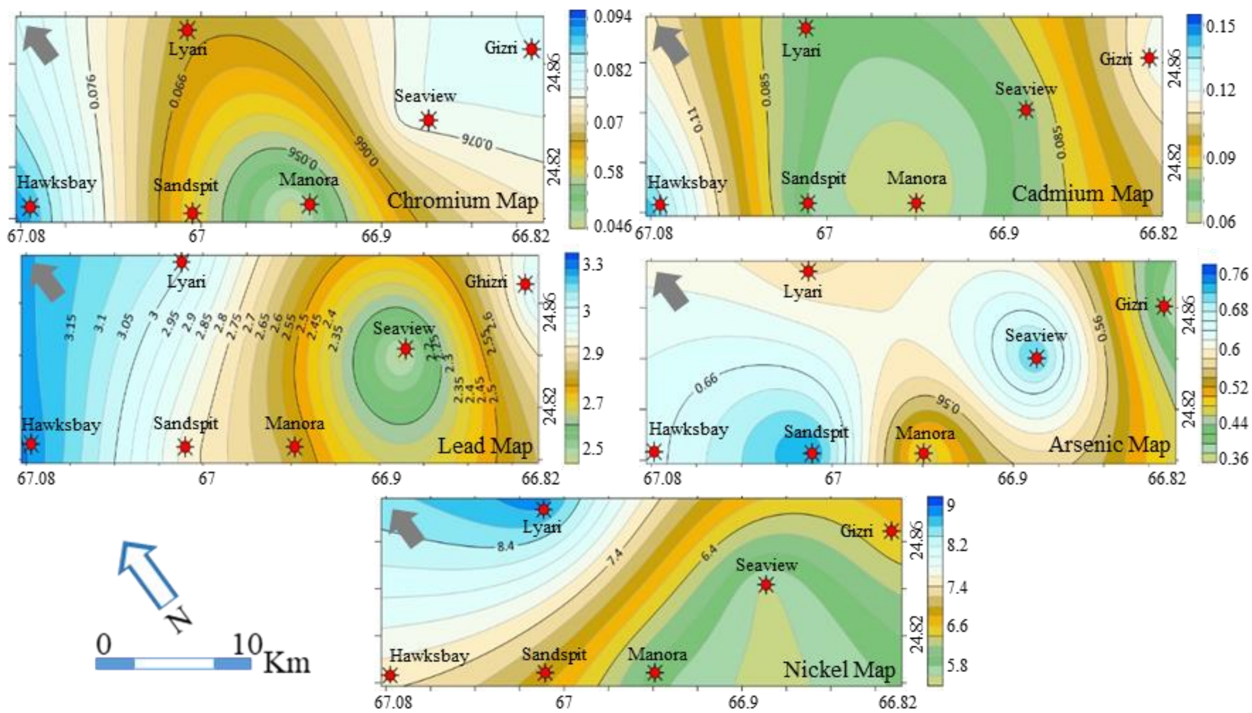


Figure 5. Spatial map of Heavy metals: a. Chromium, b. Cadmium, c. Lead, d. Arsenic, e. Nickel

The HPI analysis reveals alarming trends of pollution in the coastal water of Karachi. The HPI >100 is defined as critical heavy metal pollution. Seaview and Gizri Creek HPI> 200 shows severe heavy metal pollution. The HPI at Hawksbay Lyari, Sandspit and Manora Beach falls within the medium level but still exceeds the standard limit.

The observed values are aligned with previous studies[34]. The reported higher concentrations of Ni, Cr, Cd and Pb in surface water and sediment along Karachi coastline. The untreated effluent from the Lyari River contributes to degradation. Gizri Creek experiences low flushing due to semi enclosed bay, which intensifies pollutant accumulation[35].

The contamination level poses a serious threat to marine biodiversity. The bioaccumulation of heavy metals is toxic even at trace levels. It can severely impact the reproduction, fish growth and neurological health (Garai et al., 2021). Cd and Pb can disturb enzyme systems and trigger oxidative stress in fish and bivalves, ultimately impacting the aquatic ecosystem.

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Table 5. Heavy metal pollution index (HPI) mean value comparison with the standard HPI.

| Site | Mean HPI | Pollution Level (Observed) | Standard HPI Classification |
|---|---|---|---|
| **Seaview** | 220 | High | > 100 (**Critical Pollution)** |
| **Hawksbay** | 140 | Medium | |
| **Sandspit Beach** | 120 | Medium | |
| **Gizri Creek** | 230 | High | |
| **Manora Beach** | 110 | Medium | |
| **Lyari Outfall** | 130 | Medium | |

The forecast modelling (Figure 7) suggests that Seaview and Gizri Creek will experience critical environmental degradation by 2030 due to higher WQI & HPI thresholds. Hawksbay present shift from poor to very poor WQI and a higher risk zone for aquatic life in terms of HPI. The Manora shows relatively stable condition but WQI will be higher than the threshold limit due to urban pressure. Lyari will also face higher WQI & HPI by 2030 (Figure 6a and 6b).

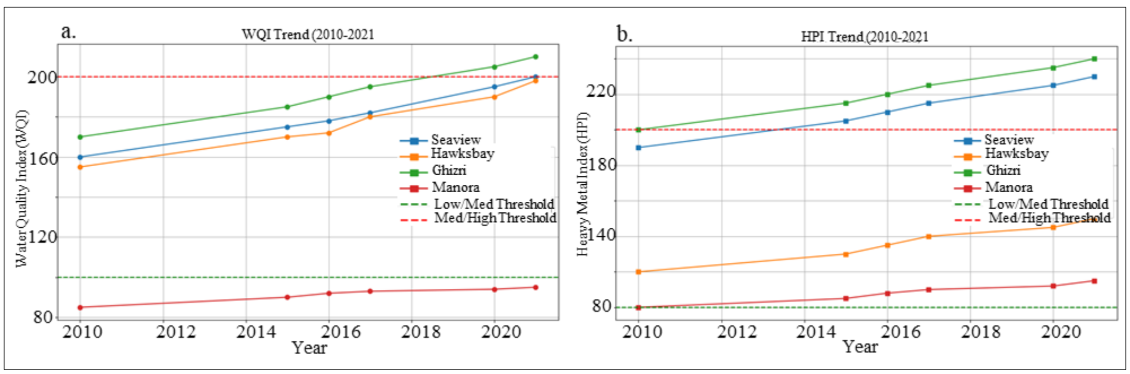


Figure 6. WQI and HPI trend from (2010-2021), representing low to high thresholds at six stations

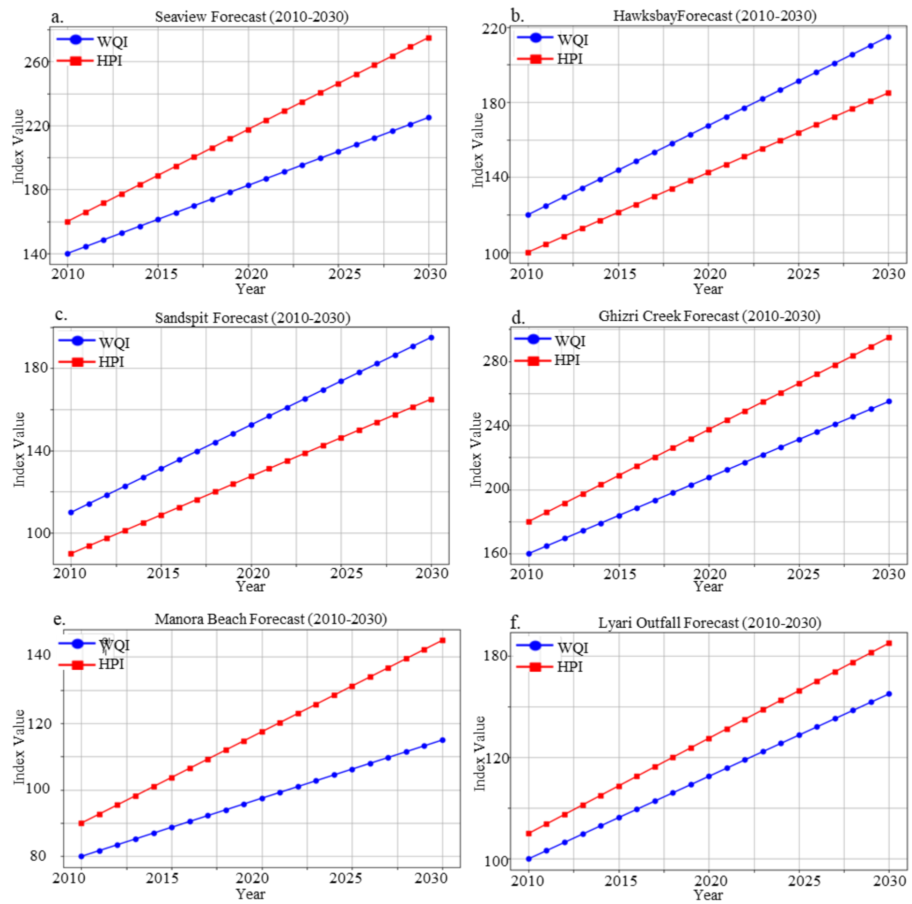


Figure 7. Forecast trend (2010-2030) of WQI and HPI for six stations

### 4.3. Statistical Analysis

The correlation matrix represents a positive relationship between COD and BOD, where r is 0.95 (Table 6). This indicates high organic contamination from industries. Lead (Pb) is correlated with Ni (r=0.8) and COD (r=0.81), highlighting industrial waste as a major source. Nickel also shows positive ties with BOD and Cr, suggesting common origins in industrial pollution. Cadmium associates moderately with Cr and Ni due to waste from batteries. Arsenic shows weak correlations, providing different sources. Generally, the presence of heavy metals is strongly connected with organic and industrial pollution.

Table 6. The correlation coefficient of observed physiochemical and Heavy metals.

| Parameter | COD | BOD | Cd | Cr | Ni | Pb | As |
|---|---|---|---|---|---|---|---|
| **COD** | 1.0 | 0.95 | 0.65 | 0.6 | 0.78 | 0.82 | 0.5 |
| **BOD** | 0.95 | 1.0 | 0.6 | 0.58 | 0.75 | 0.8 | 0.48 |
| **Cd** | 0.65 | 0.6 | 1.0 | 0.70 | 0.67 | 0.62 | 0.45 |
| **Cr** | 0.6 | 0.58 | 0.7 | 1.0 | 0.72 | 0.68 | 0.4 |
| **Ni** | 0.78 | 0.75 | 0.67 | 0.72 | 1.0 | 0.88 | 0.55 |
| **Pb** | 0.82 | 0.8 | 0.62 | 0.68 | 0.88 | 1.0 | 0.5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **As** | 0.5 | 0.48 | 0.45 | 0.4 | 0.55 | 0.5 | 1.0 |

- * Correlations > 0.7 indicate strong positive relationships (likely common sources)

## 5. Discussion

Physicochemical and heavy metal parameters from 2010–2021 across six main coastal sites of Karachi provide critical trends and pollution levels that directly influence the marine ecosystems, coastal settlement and maritime economic activities. The deterioration of water quality at Seaview and Gizri clearly represent poor-very poor WQI. The higher value of COD and BOD may suggest the influence of organic pollution from untreated discharge from industry, urbanization and port operation[36]. These elevated levels directly threaten the oxygen level, which is a critical factor for the marine ecosystem and increase the risk of hypoxia[37]. The HPI index shows the contamination of Ni, Pb and Cd beyond the max threshold limit[38]. These metals are produced largely from ship-breaking yards, industrial activities and port operations[39]. The moderate HPI for Sandspit and Lyari River is mainly influenced by urban sewage and industries[40]. The lower HPI at Manora Beach aligned with its lesser industrial effect but increased the concerns about cumulative contamination over the past decade. The forecast shows temporal variation in both WQI & HPI indicate higher pollution due to the increasing footprint of urban and industrial activities. The modelling predicts constant deterioration of water quality, especially at Seaview and Gizri Creek by 2030, risking the ecosystem, fisheries and port operations. Strategically, the coastal belt of Karachi contributes 10% in GDP of the country from maritime operations and industrial activities. Economic development has severely impacted the coastal zone in terms of land degradation, soil deterioration, air pollution and water contamination. This zone required an urgent need for integrated coastal monitoring and implementation of a mitigation plan to align with National Environmental Quality Standards and International Maritime Organization (IMO) MARPOL regulations for the maritime sector[41]. The enforcement of strict regulations on activities contributing to pollution. The monitoring stations collect real-time data for different environmental parameters in order to support sustainable maritime development. Public awareness targeting local societies and industrial stakeholders can foster collective actions. The current analysis provides a review on dataset of six stations and advanced remote sensing applications, and modelling can help to capture the pollutant dispersion and ecological impact assessment

## 6. Conclusion

This modelling of coastal water quality in Karachi over 2010–2021 highlights significant and ongoing environmental degradation, particularly at Seaview and Gizri Creek, driven by

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industrial discharges, untreated sewage, and maritime activities. The strong correlations between organic pollutants and heavy metals confirm common pollution sources, posing substantial risks to marine ecosystems, public health, and vital maritime economic sectors. Forecasting models predict continued deterioration through 2030 if current trends persist, underscoring the urgent need for integrated coastal management strategies. Compliance with international maritime pollution standards such as IMO's MARPOL regulations, improved wastewater treatment, and stringent control of ship-breaking and industrial effluents are imperative to mitigate pollution and sustain Karachi's coastal and economic vitality. This study establishes a crucial baseline for future monitoring and policymaking, advocating for coordinated efforts between governmental agencies, industry stakeholders, and local communities to ensure the sustainable development of Karachi's maritime zone and protect its valuable coastal environment.

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**Data Availability**
The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest**
The authors declare that they have no conflict of interest.

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