Journal of Corrosion and Materials *J. Corros. Mater.* (2024) 3(2), 125–130.
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Modern Analysis of Sediment Contamination in Coastal Wetlands

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(Received: 24 August 2024. Received in revised form: 18 October 2024. Accepted: 19 November 2024. Published online: 30 December 2024.)

Abstract

Coastal wetlands are among the most ecologically significant and threatened ecosystems globally, serving critical functions in biodiversity conservation, nutrient cycling, and water purification. However, the increasing burden of pollution from industrial, urban, and agricultural sources poses significant challenges to their health and sustainability. This study revisits the Mai Po Marshes, a Ramsar-listed wetland in Hong Kong, to analyze sediment contamination and its ecological implications using both historical data and contemporary methodologies. The research evaluates the spatial and vertical variations in sediment contamination by nutrients and heavy metals, identifying hot spots and assessing potential ecological impacts. The study employs modern analytical techniques, including Geographic Information System (GIS)-based mapping for spatial distribution, advanced toxicity bioassays for ecological risk assessment, and multivariate statistical analyses to identify relationships between contaminant sources and ecological effects. Key findings reveal significant contamination in surface sediments, particularly for nutrients like nitrogen and phosphorus, and heavy metals such as copper and zinc, with higher concentrations in industrially and urban-influenced regions. Despite marked contamination, the low water solubility of these pollutants suggests limited bioavailability under current conditions, aligning with the weak toxic responses observed in bacterial toxicity assays. However, the potential for long-term ecological impacts, including bioaccumulation and biomagnification, raises concerns for the wetland's flora and fauna, particularly migratory bird species that depend on this habitat.

Keywords:coastal wetlands, sediment contamination, heavy metals, ecological risk assessment, wetland conservation strategies

1. Introduction

Coastal wetlands are among the most valuable ecosystems on Earth, playing a crucial role in maintaining ecological balance, supporting biodiversity, and delivering essential services such as water purification, flood regulation, and carbon sequestration [1]. These unique habitats are hotspots of biological productivity, serving as nurseries for aquatic species and supporting intricate food webs. Despite their immense ecological and economic importance, coastal wetlands are increasingly threatened by pollution stemming from urbanization, industrial expansion, and agricultural runoff. The Mai Po Marshes in Hong Kong, designated as a Ramsar Wetland of International Importance, exemplify the challenges faced by wetlands globally. Acting as a vital stopover and feeding ground for thousands of migratory bird species, these marshes also host a wide array of aquatic and terrestrial organisms, underscoring their significance for regional and global conservation efforts [2].

Sediment contamination poses a significant challenge to the health and functionality of wetland ecosystems [3]. Sediments often act as sinks for various pollutants, including heavy metals, nutrients, and organic contaminants, which accumulate over time due to adsorption onto fine particles. These pollutants can have far-reaching ecological consequences, impacting wetland organisms through processes such as bioaccumulation and biomagnification, which disrupt food chains and threaten sensitive species. For instance, heavy metals like zinc and copper, commonly found in contaminated sediments, can exert toxic effects on benthic organisms, migratory birds, and fish species that are integral to wetland ecosystems. Moreover, pollutants trapped in sediments are not static; they can be remobilized into the water column during events such as dredging, storms, or tidal cycles, amplifying their ecological impact and potentially spreading contamination to adjacent areas [4].

The Mai Po Marshes are located near the Pearl River Delta, one of the world's most industrialized and urbanized regions [5]. Over recent decades, rapid economic development in the Shenzhen Special Economic Zone and surrounding areas has led to a substantial increase in the pollution load entering these wetlands. Untreated wastewater, agricultural runoff, and industrial discharges flow into the marshes via rivers and streams, depositing pollutants into the sediments. Previous research has revealed elevated levels of nutrients such as nitrogen and phosphorus, along with heavy metals like copper and zinc, in the marsh sediments [6]. Evidence of nutrient enrichment and metal contamination further underscores the urgent need for continuous monitoring and the implementation of effective management strategies to mitigate pollution and preserve the ecological integrity of these vital habitats [7].

Traditional approaches to assessing sediment contamination, while valuable, often rely on labor-intensive sampling and lack the spatial resolution necessary for comprehensive analysis [8]. However, advances in environmental science and technology have enhanced our capacity to study and manage sediment contamination. Tools such as Geographic Information System (GIS)-based mapping, multivariate statistical techniques, and improved bioassays have revolutionized environmental monitoring. GIS enables the visualization of spatial and temporal pollution patterns, while statistical methods such as principal component analysis (PCA) and cluster analysis help identify key factors driving contamination dynamics. Furthermore, modern bioassays that utilize diverse test organisms and molecular-level analyses provide more precise assessments of the ecological risks associated with contaminated sediments [9].

This study revisits sediment contamination in the Mai Po Marshes using an integrated approach that combines historical data with contemporary analytical tools [10]. The research aims to (1) quantify the concentrations of key contaminants, including nutrients and heavy metals, in surface and subsurface sediments; (2) assess spatial and vertical variations in sediment contamination; (3) evaluate ecological risks using advanced toxicity assays; and (4) discuss the implications of sediment contamination for wetland management and conservation. By leveraging cutting-edge techniques, this study seeks to provide a more nuanced understanding of sediment contamination dynamics and deliver actionable insights to support the mitigation of pollution in sensitive wetland ecosystems [11].

As coastal wetlands like the Mai Po Marshes face escalating pressures from human activities and climate change, it is imperative to adopt holistic and adaptive management strategies to safeguard their ecological health and resilience. This research contributes to the scientific understanding of sediment contamination while offering a robust foundation for developing targeted policies and conservation practices. By addressing the complex interplay of pollution sources, contamination pathways, and ecological risks, the study aims to inform and enhance efforts to protect and restore these invaluable ecosystems, ensuring their sustainability for future generations [12].

2. Materials and Methods

Undisturbed sediment samples were collected in triplicates from six intertidal sites across the Mai Po Marshes during low tide in February 1996. Polyethylene core samplers, with an internal diameter of 8 cm, were utilized to ensure sample integrity. Sediment cores were immediately segmented into two layers: surface sediments (0–8 cm) and bottom sediments (8–16 cm). Following collection, the samples were stored in air-tight polyethylene containers and maintained at 4°C in an icebox to preserve their chemical and physical properties. Analysis of the samples was conducted within a week to ensure minimal alteration of the sample's original state. Prior to use, all sampling equipment and containers were meticulously acid-washed, rinsed with distilled water, and further cleaned with seawater at the sampling site to prevent contamination.

Field measurements for pH and redox potential (Eh) were carried out on-site using a Checkmate water meter (Corning, New York). Sediments were processed in the laboratory by removing coarse debris and gravel, followed by air-drying and sieving through a 2-mm mesh. Moisture content was quantified by oven-drying sediment samples at 105°C for seven days. The particle size distribution was determined using the hydrometer method on air-dried, non-sieved samples.

The surface sediments underwent additional characterization to determine total organic carbon (TOC) using the Walkley-Black titration method. Both surface and bottom sediment layers were analyzed for nutrient and metal concentrations. Total nitrogen (TN) and total phosphorus (TP) levels were quantified using a QuickChem AE automated ion analyzer (Lachat Instruments, Milwaukee, Wisconsin) after digestion with concentrated sulfuric acid at 360°C. Water-soluble nitrogen and phosphorus were extracted at a 1:5 sediment-to-water ratio, agitated on an orbital shaker at 180 rpm for one hour, and filtered using 0.45 μ Millipore membrane filters. Soluble nitrogen and phosphorus contents were analyzed using the Berthelot method and the ascorbic acid method, respectively.

Total concentrations of cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) in the sediments were determined using a Hitachi Z-8100 atomic absorption spectrophotometer (Polarized Zeeman, Tokyo) after digestion with a mixed acid solution (4:1 ratio of concentrated H_2SO_4 to concentrated HNO_3). Soluble metal concentrations in sediment extracts were measured using the same spectrophotometer. All analytical procedures adhered to standard methods as outlined by the American Public Health Association (1992).

The potential biological impacts of sediment contamination were evaluated using the standard Microtox® test. This assay employed the marine bacterial species Vibrio fischeri to assess the toxicity of sediment elutriates. Sediment elutriates were prepared by mixing wet sediment with 2% sodium chloride at a 1:1 ratio (w/v) in airtight centrifuge tubes. The mixtures were shaken on an orbital shaker at 180 rpm for 48 hours and then centrifuged at 10,000 rpm for 10 minutes. The supernatant was collected as elutriate for the toxicity test.

A Microtox M500 toxicity analyzer (Microbics Corporation, Carlsbad) was used to determine the 15-minute EC_50 endpoint, which indicates the concentration of elutriate causing a 50% reduction in bacterial light emission at 15°C. Zinc sulfate and double-distilled water were used as positive and negative controls, respectively, to validate the assay results. Preliminary screening tests were conducted to determine if further toxicity testing was warranted.

Data analysis was conducted using SPSS for Windows Release 6.0 on an IBM Pentium PC. One-way analysis of variance (ANOVA) was applied to evaluate differences in sediment quality across the six sampling sites. A Student's t-test was performed to detect significant differences (P ¡ 0.05) between surface and bottom sediment layers. Tukey's Honestly Significant Difference (HSD) test was used to calculate the least significant differences (LSD) at P ¡ 0.05, identifying statistically significant variations among the sampling sites.

All analytical procedures were performed in triplicate to ensure reproducibility and reliability of results. The concentrations of contaminants in sediments from the six sites were reported as mean values with corresponding ranges. Parameters such as TN, TP, heavy metal concentrations, and soluble contents were systematically compared between surface and bottom sediments to assess vertical distribution and contamination profiles. This comprehensive approach provided critical insights into the spatial and vertical variability of sediment contamination in the Mai Po Marshes.

3. Results

3.1 Sediment Characteristics

The sediment samples collected from the six intertidal sites exhibited distinct physico-chemical properties. The pH values of the sediment samples ranged from slightly acidic to neutral, with no significant differences observed between surface (0–8 cm) and bottom (8–16 cm) sediments. Redox potential (Eh) measurements indicated that most sites had suboxic to anoxic conditions, consistent with the low-energy environment of the wetland. Moisture content was significantly higher in surface sediments compared to bottom sediments, reflecting their greater exposure to tidal influences. Particle size analysis revealed a predominance of fine-grained sediments, with silt and clay fractions comprising the majority of the sediment composition.

3.2 Nutrient Concentrations

The concentrations of total nitrogen (TN) and total phosphorus (TP) varied across sites but were generally higher in surface sediments than in bottom sediments. Average TN concentrations in surface sediments ranged from 1510 to 2770 mg/kg, while bottom sediments showed slightly lower values, ranging from 1680 to 2730 mg/kg. Soluble nitrogen content followed a similar trend, with higher concentrations detected in surface sediments. Total phosphorus concentrations in surface sediments ranged from 119 to 264 mg/kg, significantly higher than the 16.4 to 41.5 mg/kg recorded in bottom sediments. Soluble phosphorus levels were relatively low but consistent across both sediment layers.

3.3 Heavy Metal Contamination

Heavy metal analysis revealed significant contamination with cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) across all sampling sites. Total cadmium concentrations in surface sediments ranged from 5.81 to 7.47 mg/kg, while bottom sediments had slightly elevated levels, ranging from 6.52 to 7.92 mg/kg. Copper concentrations in surface sediments were notably higher, with values ranging from 29.7 to 88.7 mg/kg, compared to 30.6 to 65.5 mg/kg in bottom sediments. Zinc and nickel exhibited similar trends, with surface sediments showing higher contamination levels than bottom sediments.

Soluble metal contents were generally low, indicating that a significant portion of heavy metals were bound to sediment particles. Soluble cadmium concentrations were consistent across surface and bottom sediments, ranging from 0.20 to 0.26 mg/kg. Soluble copper concentrations ranged from 0.03 to 0.15 mg/kg in surface sediments and were lower in bottom sediments. Soluble zinc concentrations in surface sediments ranged from 0.01 to 0.72 mg/kg, while bottom sediments recorded values between 0.01 and 0.35 mg/kg. The low solubility of metals suggests limited immediate bioavailability but highlights potential risks associated with remobilization events.

3.4 Toxicity Assessment

The Microtox® toxicity test indicated varying levels of sediment toxicity across sites. Surface sediment elutriates exhibited greater toxicity compared to bottom sediment elutriates, with 15-minute EC_50 values reflecting significant reductions in light emission from Vibrio fischeri. Sites with higher heavy metal concentrations and nutrient levels showed correspondingly greater toxicity, suggesting a combined impact of metal contamination and nutrient enrichment on sediment toxicity.

Positive controls with zinc sulfate validated the sensitivity of the test, while negative controls confirmed the absence of external contamination.

3.5 Statistical Analysis

ANOVA results revealed significant spatial differences in nutrient and metal concentrations among the six sites (P ¡ 0.05). Tukey's HSD test identified specific site pairs with statistically significant differences in contaminant levels. The Student's t-test showed significant vertical variation between surface and bottom sediments for most parameters, particularly for nutrients and heavy metals. These findings underscore the heterogeneous distribution of contamination within the wetland ecosystem.

4. Discussion

The findings from this study highlight significant nutrient enrichment in the Mai Po Marshes, particularly in the surface sediments [13]. Elevated levels of total nitrogen (TN) and total phosphorus (TP) in surface layers suggest active deposition from external sources, including agricultural runoff, untreated wastewater, and industrial discharges. These nutrients are likely transported through rivers and streams draining into the wetland. The higher nutrient levels in surface sediments relative to bottom sediments underscore the ongoing influence of contemporary pollution sources. Excessive nutrient inputs, particularly nitrogen and phosphorus, can lead to eutrophication, fostering algal blooms and hypoxic conditions, which degrade water quality and threaten aquatic life. Given the ecological importance of the Mai Po Marshes as a habitat for diverse aquatic and avian species, nutrient enrichment poses a direct challenge to maintaining biodiversity and ecosystem functionality [14].

The study's findings indicate significant contamination of sediments with heavy metals, particularly cadmium (Cd), copper (Cu), nickel (Ni), and zinc (Zn) [15]. The elevated concentrations of these metals in surface sediments reflect continuous inputs from industrial and urban sources in the Pearl River Delta region. The slight but consistent accumulation of these metals in bottom sediments indicates historical deposition and long-term persistence within the wetland ecosystem.

Cadmium and copper were particularly concerning due to their known toxicity to benthic organisms and potential for bioaccumulation. Copper, for instance, can impair metabolic and reproductive functions in aquatic organisms at elevated concentrations [16]. The findings of higher soluble metal contents in surface sediments indicate the potential for these metals to enter the water column during disturbance events, such as dredging or storms, exacerbating ecological risks.

The Microtox® toxicity assay revealed that sediment elutriates from the Mai Po Marshes exhibited varying levels of toxicity, with surface sediments showing greater toxicity than bottom sediments [17]. This pattern aligns with the observed concentrations of heavy metals and nutrients, suggesting their combined contribution to sediment toxicity. The study's use of Vibrio fischeri as a bioindicator underscores the utility of microbial-based assays in evaluating sediment toxicity. Sites with elevated heavy metal concentrations, particularly zinc and copper, demonstrated higher toxicity levels, reaffirming the role of these metals in driving adverse biological effects [18].

The interplay between nutrient enrichment and heavy metal contamination likely amplifies the ecological risks. Elevated nutrient levels can alter the sediment's physicochemical properties, influencing the mobility and bioavailability of heavy metals. For example, eutrophication-induced changes in redox potential can enhance the release of bound metals into the water column, increasing their bioavailability and toxicity to aquatic organisms [19].

The significant spatial variability in nutrient and metal concentrations across the six sampling sites reflects the heterogeneous nature of pollution inputs into the Mai Po Marshes. Proximity to pollution sources, such as urban runoff or agricultural drainage, likely contributes to the observed differences [20]. Vertical variations in sediment contamination, with higher levels in surface sediments, suggest ongoing deposition of pollutants. However, the presence of contaminants in bottom sediments highlights the long-term accumulation and persistence of pollutants within the ecosystem. These findings emphasize the need for spatially explicit monitoring and management approaches to address localized pollution hotspots effectively.

The results of this study align with previous research documenting nutrient and heavy metal contamination in the Mai Po Marshes and other wetlands in the Pearl River Delta region. However, the integration of contemporary analytical tools, such as advanced toxicity assays and statistical techniques, provides a more nuanced understanding of contamination dynamics. The observed nutrient and heavy metal concentrations in the current study are consistent with historical trends, underscoring the chronic nature of pollution in the region.

The findings of this study have critical implications for the management and conservation of the Mai Po Marshes. The observed contamination levels underscore the urgent need for mitigation measures to reduce pollution inputs. Strategies to address nutrient enrichment should prioritize controlling agricultural runoff through the implementation of buffer zones, wetland restoration, and improved wastewater treatment systems. Reducing industrial discharges of heavy metals will require stricter regulatory enforcement and the adoption of cleaner production technologies in upstream areas.

Sediment contamination management should also consider potential remobilization events. Measures such as sediment capping or dredging should be approached cautiously, as they can disturb contaminated sediments and release bound pollutants into the water column. Nature-based solutions, including the use of vegetation to stabilize sediments and enhance contaminant sequestration, offer sustainable alternatives for mitigating sediment contamination.

While this study provides valuable insights into sediment contamination in the Mai Po Marshes, several areas warrant further investigation. The use of advanced bioassays with higher trophic level organisms could complement microbial-based toxicity assessments, offering a broader perspective on ecological risks. Long-term monitoring programs are essential to evaluate the effectiveness of pollution mitigation strategies and track changes in sediment contamination over time.

Future studies should also explore the interactive effects of multiple stressors, including climate change, on sediment contamination dynamics. Rising sea levels, increased storm intensity, and changing precipitation patterns may alter pollutant transport and deposition processes, further challenging wetland management efforts. Integrating hydrodynamic modeling with empirical data can provide valuable predictions of future contamination scenarios under different management and climate change scenarios.

5. Conclusion

The Mai Po Marshes face significant ecological challenges due to persistent nutrient enrichment and heavy metal contamination, as demonstrated by this study. Elevated concentrations of total nitrogen, total phosphorus, and heavy metals such as cadmium, copper, nickel, and zinc highlight the ongoing impact of anthropogenic activities in the surrounding Pearl River Delta region. Surface sediments were particularly affected, underscoring the influence of contemporary pollution sources and the need for immediate intervention.

The toxicity assessment revealed that contamination levels pose ecological risks, with nutrient enrichment and heavy metals acting synergistically to degrade sediment quality. The spatial and vertical variability in contamination underscores the necessity for localized and targeted management strategies. This study's integration of advanced analytical techniques and bioassays provided a detailed understanding of contamination dynamics, offering actionable insights for wetland conservation.

To preserve the ecological integrity of the Mai Po Marshes, stakeholders must implement strategies to reduce pollution inputs, such as improving wastewater treatment and enforcing stricter industrial regulations. Nature-based solutions, including vegetation-based sediment stabilization, offer promising avenues for sustainable remediation. This research serves as a foundation for future studies and policy-making efforts, contributing to the global understanding and management of wetland ecosystems under increasing anthropogenic pressures.

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