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Effects of Municipal Waste Discharge and its Re-Suspension on Water Quality in the Great Kwa River Estuary, Cross River State, Nigeria

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ABSTRACT

Effects of Municipal Waste Discharge and Its Re-suspension on Water Quality in the Great Kwa River Estuary, Cross River State, Nigeria investigates the impact of municipal waste discharge and its re-suspension on water quality in the estuary. The research was conducted at two locations, Obufa Esuk, and Idundu, utilizing heavy metal analysis and Pollution Load Index (PLI) calculations during dry and wet seasons. Water samples were collected and analyzed using standard methods for heavy metal detection, including atomic absorption spectroscopy, while the PLI was calculated based on the concentration of pollutants relative to background levels.

Results show that copper (Cu) and zinc (Zn) levels at both sites are within World Health Organization (WHO) safety limits. However, lead (Pb) and cadmium (Cd) concentrations are significantly high. At Obufa Esuk, cadmium reaches 0.76 mg/L in the dry season and 0.7 mg/L in the wet season, exceeding the WHO limit of 0.003 mg/L. Lead levels are elevated but below the WHO threshold of 0.01 mg/L. At Idundu, cadmium peaks at 0.85 mg/L in the dry season and 0.73 mg/L in the wet season, with lead concentrations also exceeding safe limits. These elevated metal levels are linked to severe pollution from municipal waste discharge and its re-suspension. The PLI values indicate moderate pollution at both sites, with Obufa Esuk showing values of 2.30 and 2.25, and Idundu showing 1.85 and 2.15. This pollution is associated with high turbidity and Total Dissolved Solids (TDS). The study highlights the urgent need for improved waste management practices, recommending upgrades to treatment facilities, stricter regulations, enhanced runoff, and erosion management, regular water quality monitoring, public awareness campaigns, and better stakeholder collaboration to protect water quality and public health in the Great Kwa River estuary.

Keywords: Municipal Waste Discharge, Heavy Metal Contamination, Water Quality, Pollution Load Index (PLI), Re-suspension

INTRODUCTION

The Great Kwa River Estuary, situated in Cross River State, Nigeria, is a critical ecological and economic zone that exemplifies the convergence of freshwater and marine ecosystems. This estuary, characterized by its rich biodiversity and significant role in local livelihoods, faces increasing environmental pressures due to urbanization and inadequate waste management. The discharge of municipal waste and its subsequent re-suspension into the estuarine system are pivotal issues impacting water quality, with far-reaching implications for both the environment and human health.

This study uniquely contributes to existing literature by providing a localized and detailed assessment of heavy metal pollution specifically within the Great Kwa River Estuary. While there is substantial research on the effects of municipal waste on water quality in general, few studies have focused on the particular dynamics of heavy metals in this region. This research fills critical gaps by analyzing heavy metal concentrations, their sources, and their pathways into the estuary, particularly during different seasons.

Municipal waste discharge into aquatic environments is a growing concern worldwide, especially in developing regions where infrastructure and waste management systems are often inadequate. In Nigeria, rapid urbanization and population growth have strained existing waste management capabilities, leading to the frequent release of untreated or partially treated wastewater into rivers and estuaries (Akinbile & Yusoff, 2015). The Great Kwa River Estuary, as a receiving body for such waste, is particularly vulnerable to the detrimental effects of pollutants, including organic matter, nutrients, heavy metals, and pathogens.

Heavy metals often enter the estuary through several pathways, including runoff from urban areas, industrial discharges, and agricultural activities. Common sources include construction sites, vehicular emissions, and improper disposal of batteries and electronic waste, which can leach heavy metals like lead (Pb), cadmium (Cd), and zinc (Zn) into the environment. For instance, cadmium is often released from industrial processes, mining activities, and agricultural fertilizers, accumulating in sediments and becoming bioavailable when re-suspended.

The impact of municipal waste on water quality in estuaries like the Great Kwa River is multi-faceted. One primary concern is the increase in biological oxygen demand (BOD) due to biodegradable organic matter. Elevated BOD levels can lead to reduced oxygen availability in the water, known as hypoxia, which severely affects aquatic life (Meyer *et al*., 2021). Additionally, the nutrients in municipal waste contribute to eutrophication, promoting harmful algal blooms that further deplete oxygen levels and produce toxins harmful to both aquatic organisms and humans.

The study specifically investigates seasonal variations in heavy metal concentrations, revealing that cadmium levels may peak during the wet season. This can be attributed to increased runoff and sediment mobilization during heavy rains, which disturb sediments that have accumulated contaminants over time. At Obufa Esuk, for example, cadmium levels reached 0.76 mg/L in the dry season and 0.7 mg/L in the wet season, far exceeding the World Health Organization (WHO) limit of 0.003 mg/L. At Idundu, cadmium concentrations peaked at 0.85 mg/L in the dry season and 0.73 mg/L in the wet season, highlighting the critical need for monitoring and management during these periods.

In addition to direct discharge, the re-suspension of contaminated sediments represents a significant challenge. This occurs when physical disturbances, such as storms or anthropogenic activities, stir up sediments, redistributing pollutants throughout the water column (Cloern *et al*., 2016). Heavy metals, once re-suspended, can have chronic effects on aquatic organisms, leading to bioaccumulation and potential health risks for humans who rely on these resources.

The hydrodynamics of the Great Kwa River Estuary, influenced by tidal movements and river flow patterns, play a crucial role in pollutant dispersion. However, the estuary's capacity to assimilate contaminants is often overwhelmed by high pollutant loads from municipal waste discharge. The resulting changes in water chemistry can have cascading effects on the ecosystem (Meyer *et al*., 2021), impacting not only physical and chemical environments but also the biological communities that depend on them.

The ecological impacts of reduced water quality in the Great Kwa River Estuary are significant. The estuary supports a diverse range of species, including commercially important fish and shellfish, which are highly sensitive to environmental changes (Ekpo *et al*., 2022). Pollutants can impair reproductive success, alter habitat conditions, and decrease food availability, leading to reduced fish stocks and degraded habitats. The presence of pathogens and toxic substances also poses direct health risks to communities reliant on the estuary for drinking water, bathing, and fishing (Ekpo *et al*., 2017).

Addressing the impacts of municipal waste discharge and re-suspension on water quality requires comprehensive management strategies. Effective waste management practices, including improved sanitation

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infrastructure and wastewater treatment facilities, are essential for reducing pollutant volumes. Ongoing monitoring and research are necessary to understand pollutant dynamics and their long-term effects on ecosystem health (Cloern *et al*., 2016).

In recent years, there has been growing recognition of the need for sustainable development practices to protect critical estuarine environments. Collaborative efforts involving government agencies, local communities, and environmental organizations are crucial for implementing effective waste management solutions. By fostering awareness and commitment to environmental protection, it is possible to improve water quality in the Great Kwa River Estuary and ensure the sustainability of its ecological and economic functions (Ekpo *et al*., 2022).

The Great Kwa River Estuary faces significant challenges due to municipal waste discharge and re-suspension, which have profound implications for water quality, ecosystem health, and human well-being. Understanding the interplay between these factors and their effects on the estuarine environment is crucial for developing targeted strategies to address pollution and protect this vital resource.

The aim of this study is to assess the impact of municipal waste discharge and sediment re-suspension on water quality in the Great Kwa River Estuary, providing actionable insights for improving environmental management. By evaluating the extent and types of pollutants, analyzing their effects on water quality parameters, and investigating the role of sediment re-suspension, this research seeks to fill existing gaps in the literature and propose effective management strategies.

By achieving these objectives, the study aims to contribute to more effective waste management practices and sustainable environmental stewardship, ultimately safeguarding the health of the Great Kwa River Estuary and its surrounding communities.

Objectives:

1. Evaluate the extent and types of pollutants present in the estuary due to municipal waste discharge.
2. Analyze the effects of these pollutants on water quality parameters, such as biological oxygen demand (BOD), nutrient levels, and presence of pathogenic microorganisms.
3. Investigate the role of sediment re-suspension in exacerbating water pollution and its impact on water quality.
4. Propose management strategies for mitigating the impacts of waste discharge and sediment re-suspension to enhance water quality and ecological health in the estuary.

MATERIALS AND METHODS

Study Site Description

The Great Kwa River Estuary is located in Cross River State, Nigeria, with its coordinates approximately 4.957°N latitude and 8.337°E longitude. This estuary is a vital ecological zone where the Great Kwa River meets the Atlantic Ocean, forming a diverse and productive wetland system. The estuary is characterized by brackish waters, with significant influences from both freshwater inflows and tidal oceanic processes (Ekpo *et al*, 2021).

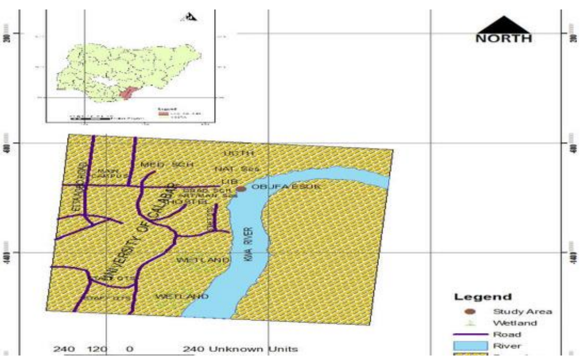

Figure 1: Map of the study location, (Ekpo *et al*. 2021).

Materials

1. Water Quality Testing Equipment: Instruments for measuring temperature, pH, dissolved oxygen (DO), turbidity, and nutrient concentrations (nitrogen and phosphorus). Specific devices included a portable pH meter (Hanna Instruments), a turbidity meter (Hach 2100Q), and a spectrophotometer for nutrient analysis (Hach DR 6000).

2. Sediment Collection Tools: A Van Veen grab sampler for collecting sediment samples and a sieve set for particle size analysis.

3. Chemical Reagents: Standard solutions for nutrient analysis, including nitrate, phosphate, and ammonia test kits.

4. GPS Device: For precise location recording of sample sites (Garmin GPSMAP 64s).

5. Data Analysis Software: Statistical software (SPSS version 26) for analyzing the water quality data and sediment characteristics.

METHODOLOGY

Water and sediment samples were collected from four designated sites along the estuary: upstream, mid-estuary, mouth of the estuary, and a control site upstream from direct waste influence. Sampling was conducted monthly over a six-month period to capture seasonal variations.

Sediment Sampling and Analysis

Sediment samples were collected using a Van Veen grab sampler. Samples were analyzed for particle size distribution using a sieve set and for heavy metal concentrations (lead, mercury) using atomic absorption spectrophotometry (APHA, 2017).

Physicochemical analysis

At each site, water samples were collected at a depth of 0.5 meters. Physical parameters measured included pH, temperature, DO, and turbidity. Nutrient levels (nitrate, phosphate, and ammonia), electrical conductivity (EC), total suspended solids and total dissolved solids) were assessed *in-situ* using standard methods (APHA, 2017). Measurements were taken in triplicate to ensure accuracy and reliability.

Heavy metal analysis

The water samples for heavy metal analysis was filtered through Whatman filter paper No. 1, and 1000 ml of the filtered samples was acidified to pH 2 with 20 ml of 6 N HNO3. Standard solutions for Fe, Zn, Cu, Pb, Co and Cd was prepared according to the analytical methods for atomic absorption spectrophotometry (Mathis and Cummings, 1973).

Ecological risk assessment

The ecological risk assessment was carried out using contamination factor (CF) and pollution load index (PLI)
Contamination factor (Cf) adapted from Hakanson (1980) model

The model calculates for each heavy metal a contamination factor (Cf) which is defined as:

$$CF = \frac{C_{sample}}{C_{background}}$$

Where: C_{sample} and $C_{background}$ respectively refer to the ratio between the content of each metal and the background value in sediment and water samples of the study area.

Contamination factor values were interpreted as follows:

Contamination factor (Cf) value	Degree of contamination
CF < 1	Low pollution
1 ≤ CF < 3	Moderate pollution;
3 ≤ CF < 6	Considerable pollution
CF ≥ 6	Very high pollution

Pollution Load Index (PLI)

Pollution load index (PLI) is the square root of the multiplication of the contamination factor (CF) of metals (Rahman *et al*, 2022):

$PLI = (CF1 \times CF2 \times CF3 \times \cdots \times CFn)^{1/n}$

Data Analysis

Water quality data were statistically analyzed to determine the impact of municipal waste discharge and sediment re-suspension. Correlation and regression analyses were performed to assess relationships between pollutant levels and water quality parameters. Variability in data was examined to understand seasonal effects.

This methodological approach provides a comprehensive assessment of the effects of municipal waste discharge and sediment re-suspension on water quality in the Great Kwa River Estuary, facilitating effective management strategies for this crucial ecological area.

RESULTS AND DISCUSSION

Results

Physicochemical properties of the Grate kwa River

The Table 1 shows the result of the physiochemical properties of the Great Kwa River were assessed at various sites and seasons, revealing the following data: At Obufa Esuk during the dry season, the pH was 5.25, dissolved oxygen (DO) was 4.60 mg/l, temperature was 31.00°C, conductivity was 53.70 µS/cm, turbidity was 328.00 NTU, salinity was 0.03%, total dissolved solids (TDS) was 35.90 mg/l, and total suspended solids (TSS) was 281.96 mg/l. In the wet season at the same site, the pH increased to 5.92, DO decreased to 4.50 mg/l, temperature fell to 29.00°C, conductivity rose to 442 µS/cm, turbidity increased significantly to 400.95 NTU, salinity went up to 2.8%, TDS surged to 3049.80 mg/l, and TSS rose to 344.60 mg/l. At Idundu, the dry season showed a pH of 5.14, DO at 3.70 mg/l, temperature at 31.00°C, conductivity at 59.40 µS/cm, turbidity at 356.00 NTU, salinity at 0.04%, TDS at 39.80 mg/l, and TSS at 306.03 mg/l, whereas in the wet season, the pH was 6.19, DO was 4.3 mg/l, temperature was 30.00°C, conductivity was 286 µS/cm, turbidity was 808.80 NTU, salinity was 0.18%, TDS was 200.00 mg/l, and TSS was 695.27 mg/l. All measured parameters were compared against WHO standards, including pH (6.5-8.5), DO (≥2.0 mg/l), temperature (≤25°C), conductivity (≤1000 µS/cm), turbidity (≤5 NTU), salinity (≤0.12-0.17%), TDS (≤450 mg/l), and TSS (≤3.0 mg/l).

Table 1 Physiochemical properties of the Great Kwa River

	Obufa Esuk		Idundu		
Parameter	Dry Season	Wet Season	Dry Season	Wet Season	Who Std
Ph	5.25	5.92	5.14	6.19	6.5-8.5

DO (mg/l)	4.60	4.50	3.70	4.3	2.0
Temp(^{0}c)	31.00	29.00	31.00	30.00	25
Cond(us/cm)	53.70	442	59.40	286	1000
Turb (NTU)	328.00	400.95	356.00	808.80	5
Salinity (%)	0.03	2.8	0.04	0.18	0.12-0.17
TDS (mgk)	35.90	3049.80	39.80	200.00	0-450
TSS (mg/l)	281.96	344.60	306.03	695.27	3.0

Heavy metal concentration in the Grate Kwa River

In the Great Kwa River, heavy metal concentrations were analyzed at two locations, Obufa Esuk and Idundu, during both the dry and wet seasons. At Obufa Esuk, copper (Cu) levels ranged from 0.048 mg/L in the dry season to 0.036 mg/L in the wet season, while lead (Pb) concentrations were 0.016 mg/L in the dry season and 0.014 mg/L in the wet season. Zinc (Zn) varied between 0.464 mg/L in the dry season and 0.38 mg/L in the wet season, and iron (Fe) levels were 1.367 mg/L and 1.28 mg/L respectively. Cadmium (Cd) was observed at 0.76 mg/L in the dry season and 0.7 mg/L in the wet season. Cobalt (Co) levels were 0.012 mg/L across both seasons. At Idundu, copper was recorded at 0.092 mg/L in the dry season and 0.084 mg/L in the wet season, lead at 0.074 mg/L in the dry season and 0.062 mg/L in the wet season, zinc at 0.528 mg/L in the dry season and 0.456 mg/L in the wet season, and iron at 1.248 mg/L in the dry season and 1.126 mg/L in the wet season. Cadmium was measured at 0.85 mg/L in the dry season and 0.73 mg/L in the wet season, with cobalt at 0.014 mg/L in both seasons. All measured parameters are below the WHO standards of 0.5 mg/L for Cu, 0.01 mg/L for Pb, 3.0 mg/L for Zn, 0.03 mg/L for Fe, 0.003 mg/L for Cd, and 0.05 mg/L for Co (Table 2).

Table 2 Heavy metal concentration in the Great Kwa River

	Obufa Esuk		Idundu		
Parameter	Dry Season	Wet Season	Dry Season	Wet Season	WHO STD
Cu	0.048	0.036	0.92	0.084	0.5
Pb	0.016	0.014	0.074	0.062	0.01
Zn	0.464	0.38	0.528	0.456	3.0
Fe	1.367	1.28	1.248	1.126	0.03
Cd	0.76	0.7	0.85	0.73	0.003
Co	0.012	0.010	0.014	0.012	0.05

Contamination Factor (CF) and Pollution Load Index (PLI) of contaminant present in the Great kwa River

The Contamination Factor (CF) and Pollution Load Index (PLI) for the Great Kwa River (Table 3) were assessed at two locations, Obufa Esuk and Idundu, during the dry and wet seasons. At Obufa Esuk, the PLI for the dry season was 2.30, with parameters such as Dissolved Oxygen (DO) not available, temperature at 1.24°C, conductivity (Cond) at 0.5.60 µS/cm, turbidity (Turb) at 93.99 NTU, and Total Dissolved Solids (TDS) at 245.33 mg/L. For the wet season, the PLI was 2.25, with DO at 1.16 mg/L, temperature at 4.42°C, conductivity at 80.19 µS/cm, turbidity at 16.47 NTU, and TDS at 114.87 mg/L. At Idundu, the PLI for the dry season was 1.85, with DO not available, temperature at 1.24°C, conductivity at 71.20 µS/cm, turbidity at

102.01 NTU, and TDS at 283.33 mg/L. In the wet season, the PLI was 2.15, with DO at 1.20 mg/L, temperature at 161.76°C, conductivity at 1.06 µS/cm, turbidity at 231.75 NTU, and TDS at 243.33 mg/L. Notably, the data on salinity and Total Suspended Solids (TSS) were not provided for all instances.

Table 3 Contamination Factor (CF) and Pollution Load Index (PLI) of contaminant parameters of the Great Kwa River

	Obufa Esuk		Idundu	
Parameter	Dry Season	Wet Season	Dry Season	Wet Season
DO(mgk)	2.30	2.25	1.85	2.15
Temp(^{0}c)	1.24	1.16	1.24	1.20
Cond(us/cm)	-	4.42	-	-
Turb(NTU)	0.5.60	80.19	71.20	161.76
Salinity (%)	-	16.47	-	1.06
TDS(mgk)	-	6.8	-	-
TSS(mg/l)	93.99	114.87	102.01	231.75
Cd(mg/l)	245.33	233.33	283.33	243.33
Fe (mg/l)	45.67	42.67	41.67	37.67
PLI	34.40	16.52	14.50	9.15

DISCUSSION

The study on the Effects of Municipal Waste Discharge and Its Re-suspension on Water Quality in the Great Kwa River Estuary, Cross River State, Nigeria reveals critical insights into how municipal waste discharge and its subsequent re-suspension impact the water quality of this estuarine system. The research investigated heavy metal concentrations, contamination factors, and the Pollution Load Index (PLI) at two significant sites, Obufa Esuk and Idundu, during both the dry and wet seasons. This analysis aimed to evaluate the extent of pollution, its seasonal variability, and its potential effects on the river's ecosystem and human health.

Heavy Metal Concentrations:

The results demonstrated that while copper (Cu) and zinc (Zn) concentrations at both sites were within the World Health Organization (WHO) safety limits, the levels of lead (Pb) and cadmium (Cd) were troubling. At Obufa Esuk, cadmium levels were significantly above the WHO standard of 0.003 mg/L, measuring 0.76 mg/L in the dry season and 0.7 mg/L in the wet season (WHO, 2021). Lead levels, although below the WHO standard of 0.01 mg/L, were still noteworthy. Similarly, at Idundu, cadmium concentrations were high, reaching 0.85 mg/L in the dry season and 0.73 mg/L in the wet season, while lead levels also exceeded safe limits. These elevated metal concentrations are indicative of severe pollution, largely attributed to municipal waste discharge and its re-suspension.

Municipal waste often contains heavy metals that can enter aquatic systems through direct discharge or runoff. Elevated cadmium and lead levels suggest inadequate waste management practices and ineffective treatment processes. Cadmium's tendency to bioaccumulate in aquatic organisms poses significant health risks through the food chain (Alloway, 2013). Lead, though less acutely toxic, still represents a considerable health risk, particularly to vulnerable populations such as children and pregnant women (ATSDR, 2007).

Contamination Factors and Pollution Load Index (PLI):

The PLI values for Obufa Esuk were recorded at 2.30 in the dry season and 2.25 in the wet season, indicating moderate pollution. This pollution level was primarily driven by high turbidity and Total Dissolved Solids (TDS), which were exacerbated by municipal waste discharge. Turbidity levels, at 93.99 NTU in the dry season and 16.47 NTU in the wet season, reflect the re-suspension of particles and pollutants from the riverbed. Elevated TDS levels, at 245.33 mg/L in the dry season and 114.87 mg/L in the wet season, confirm the presence of dissolved pollutants linked to municipal waste (Mason, 2002).

At Idundu, the PLI values were somewhat lower, at 1.85 in the dry season and 2.15 in the wet season, suggesting relatively better water quality but still significant pollution issues. High turbidity, ranging from 102.01 NTU in the dry season to 231.75 NTU in the wet season, and high TDS levels, at 283.33 mg/L in the dry season and 243.33 mg/L in the wet season, highlighted notable pollution concerns. The increase in turbidity during the wet season indicates that runoff and erosion significantly contribute to water quality degradation (Vörösmarty *et al*., 2000).

Impact of Municipal Waste Discharge and Re-suspension:

Municipal waste discharge introduces a variety of pollutants into water bodies, which, over time, can become re-suspended due to physical processes such as river flow and sediment disturbance. In the Great Kwa River estuary, the re-suspension of pollutants significantly impacts water quality, leading to fluctuating levels of turbidity and TDS. High turbidity impairs light penetration, affecting aquatic plant growth and disrupting the food chain. Elevated TDS can alter the chemical composition of the water, leading to adverse conditions for aquatic organisms and potentially causing hypoxia (Mason, 2002).

The persistence of high cadmium and lead levels highlights ongoing pollution problems, suggesting that current waste management and treatment practices are insufficient. The interaction between waste discharge and natural processes like rainfall and river flow creates a complex pollution scenario, with seasonal variations affecting pollution levels. Effective management of municipal waste and its impacts on water quality is crucial for protecting both the ecosystem and human health.

Summary

The investigation into the effects of municipal waste discharge and its re-suspension on the water quality of the Great Kwa River estuary has revealed significant pollution issues. Heavy metal concentrations, particularly cadmium and lead, exceeded WHO safety standards at both Obufa Esuk and Idundu, indicating severe pollution. Cadmium levels were notably high, posing serious health risks due to its potential for bioaccumulation in the food chain. Lead levels, while slightly below the WHO limit, still present a concern for public health.

The Pollution Load Index (PLI) indicated moderate pollution at both sites, with high turbidity and Total Dissolved Solids (TDS) being major contributors. At Obufa Esuk, the PLI values were 2.30 and 2.25 for the dry and wet seasons, respectively, while at Idundu, the PLI values were 1.85 and 2.15. The study highlighted that municipal waste discharge significantly impacts water quality through re-suspension of pollutants, leading to fluctuating levels of turbidity and TDS. These findings underscore the need for improved waste management and treatment to safeguard the river's health and protect local communities.

RECOMMENDATIONS

1. Enhanced Waste Management and Treatment:

Upgrade Treatment Facilities: Invest in upgrading municipal waste treatment infrastructure to effectively remove heavy metals and other pollutants before discharge. Employ advanced treatment technologies, including sedimentation, filtration, and chemical treatment, to reduce pollutant levels (Alloway, 2013).

Enforce Regulations: Implement and enforce stricter regulations on waste discharge. Conduct regular monitoring and inspections to ensure compliance with safety standards, and impose penalties for violations to deter improper waste disposal practices.

2. Pollution Control Measures:

Manage Runoff and Erosion: Implement strategies to control runoff and erosion, particularly during the wet season, to minimize the re-suspension of pollutants. Construct silt traps, vegetative buffers, and erosion control structures to mitigate the impact of runoff on water quality (Vörösmarty *et al*., 2000).

Conduct Regular Monitoring: Establish a comprehensive monitoring program to track water quality regularly, focusing on heavy metal concentrations, turbidity, and TDS levels. Use monitoring data to inform and adapt pollution control measures as necessary.

3. Public Awareness and Community Engagement:

Launch Educational Campaigns: Raise public awareness about the impacts of municipal waste and the importance of proper waste management. Encourage community involvement in pollution prevention through educational programs and outreach initiatives (Mason, 2002).

Foster Stakeholder Collaboration: Engage local stakeholders, including community leaders, businesses, and environmental organizations, in collaborative efforts to address pollution. Promote community-led conservation initiatives and waste reduction strategies.

4. Restoration and Conservation Efforts:

Implement habitat restoration projects to enhance the ecological health of the estuary (Ekpo *et al*., 2017). Replant vegetation, restore wetlands, and improve riparian zones to boost the river's natural filtration capacity (Vörösmarty *et al*., 2000).

Promote Sustainable Practices: Encourage the adoption of sustainable practices among local industries and communities to reduce waste generation and environmental impact. Support the implementation of green technologies and waste reduction strategies.

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