Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 5203 – 5238 (2025)
www.ejabf.journals.ekb.eg

Assessment of Some Heavy Metals in Ashtum El- Gamil Wetland, Northen-East of the Nile Delta Coast

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ARTICLE INFO

Article History:
Received: March 24, 2025
Accepted: July 13, 2025
Online: Aug. 11, 2025

Keywords:
Aquatic ecosystems,
Manzala wetland,
Ashtum El-Gamil,
Heavy metals,
Pollution

ABSTRACT

This study was conducted to assess the concentrations of potentially harmful elements in various environmental matrices—water, sediments, aquatic plant species, fish, and a bird species—within the Ashtum El-Gamil Protectorate, a critical wetland ecosystem along the Egyptian Mediterranean coast. Physicochemical parameters and heavy metal concentrations in water samples were generally within the permissible limits established by the Egyptian Environmental Law No. 4/1994 **(ECS, 1994)**, except for cadmium, which exceeded the permissible level at Site 2. Sediment analysis revealed the following order of heavy metal accumulation: Pb > Cd > Zn, indicating potential long-term contamination risks. Bioaccumulation patterns varied among the studied plant species. *Typha domingensis* and *Halocnemum strobilaceum* exhibited the same accumulation order: Cd > Zn > Pb, whereas *Phragmites australis* and *Eichhornia crassipes* showed Zn > Pb > Cd. In fish samples (*Oreochromis niloticus*), cadmium and lead were not detected, and zinc concentrations remained within acceptable safety limits, suggesting minimal risk to aquatic food chains at the time of sampling. In contrast, the Cape cormorant (*Phalacrocorax capensis*), used as a sentinel species, showed cadmium levels exceeding the World Health Organization (WHO) allowable limits, while zinc remained below the threshold, and lead was undetected in liver tissues. These findings highlight localized bioaccumulation of cadmium in top trophic-level organisms. It is worth noting that recent dredging and restoration activities were conducted in the lake to improve water circulation and habitat conditions. Overall, this study provides valuable insights into the spatial distribution and ecological behavior of heavy metals in a sensitive wetland environment. The results underline the importance of regular monitoring and ecological risk assessment, particularly for higher trophic-level organisms, to support the sustainable management and conservation of protected wetland areas.

INTRODUCTION

One of the major global environmental concerns is water pollution, caused by the accumulation of heavy metals from industrial activities or rock erosion. The health of consumers may be adversely affected by the consumption of aquatic species contaminated by these heavy metals and originating from such environments **(Khaled *et***

***al*., 2020; Ibrahim & Mosaad, 2021)**. Cadmium (Cd) is particularly harmful due to its high toxicity potential even at low doses, environmental persistence, and ability to bioaccumulate in aquatic organisms. Since the body cannot metabolize Cd, it accumulates in the soft tissues of aquatic biota, becoming toxic over time. The bioaccumulation of Cd also contaminates the food chain, affecting all ecological processes.

Recently, increasing populations in African countries such as Egypt have heightened the focus on ensuring adequate food supplies **(Helmy *et al*., 2018; Panigrahi *et al*., 2021; Mahjoub *et al*., 2021)**. Fish, in particular, face significant risks from mercury contamination **(Drąg-Kozak *et al*., 2019)**. Worldwide, there is growing concern over the contamination of lake systems due to human activities. Manzala Lake, the largest coastal-deltaic lake in northern Egypt, has a profound impact on local communities **(Redwan & Elhaddad, 2022)**.

Due to their environmental persistence, high toxicity, and capacity for bioaccumulation, toxic heavy metals (HMs) are frequently present in the environment, posing serious threats to aquatic life and water quality. Contamination of lake bottom sediments by heavy metals is a major environmental science problem, as these metals can be both biotically harmful and long-lasting in the ecosystem **(Xu *et al*., 2017)**. Several factors contribute to the penetration of HMs into aquatic ecosystems, including sewage effluents, road traffic emissions, smelting, agriculture, industrial discharges, and combustion processes **(Rajeshkumar *et al*., 2018)**.

Exposure to HMs has been linked to various health issues, such as cancer, intellectual and developmental disorders, reduced intelligence, kidney damage, and stillbirth **(Alomary & Belhadj, 2007; Rinklebe *et al*., 2019)**. Lake Manzala receives drainage water from six large, heavily polluted drains—Faraskur, Hadous, Bahr El-Baqar, El-Serw, Mataria, and Ramsis—which collectively discharge over 4,000 million m^3 of wastewater annually **(Hegazy *et al*., 2016)**. The ability of HMs to bioaccumulate in food chains, along with their persistence, teratogenicity, mutagenicity, and carcinogenicity, makes them some of the most critical pollutants in aquatic ecosystems **(Karimi *et al*., 2020; Zhao *et al*., 2020)**.

With a surface area exceeding 1,000 km^2, Lake Manzala is the largest of Egypt's northern coastal lagoons and an important habitat for wildlife and fisheries. Surrounded by wetlands on three sides, it is separated from the Mediterranean Sea by a low sandy bar (1–2 m high) and is located in the eastern coastal Nile Delta, shared by the governorates of Damietta, Dakahlia, Sharkia, Port Said, and Ismailia. The lake stretches 50 km in length and up to 30 km in width **(Elmorsi *et al*., 2017)**.

Lake Manzala's water sources include:

1. **Exchange canals** such as Al-Sufra (north), Al-Jamil (old and new), Bughaz Al-Raswa, and Al-Qubouti (east), which allow seawater to mix with freshwater.
2. **Freshwater-rich inputs** from numerous drains and pumping stations.

3. **Wastewater discharges** from seven main drains—Farskoor, Al-Anani, Al-Serw, Jamaliah, Matariya, Hados, and Ramses—which are major sources of heavy metals and nutrients **(Hamed *et al*., 2013)**.

Prime Minister's Decision No. 459/1988 designated Ashtoum El-Gamil and Tennis Island as protected areas, covering 30 km². This was later expanded to 180 km² under Resolution No. 2780/1998. Ashtoum El-Gamil, located in the northwest of Lake Manzala, includes both the old and new El-Gamil inlets. The ancient island of Tennis, southwest of Port Said, covers about 8 km² and is surrounded by water. Freshwater enters from the south through agricultural drains such as Cypress, Hadous, and Ramses, as well as through sewage drains like Bahr al-Baqar and Eniniya. Saltwater enters from the Mediterranean via the Al-Jamil inlet to the north.

The lake receives over 1.5 million m³ of wastewater daily, including more than 1.25 million m³ from Greater Cairo. Since none of these drainage sources lie within the Ashtoum El-Gamil Reserve boundaries, the managing authority cannot control them **(Abdel Karim, 2008)**. The protected area aims to safeguard pregnant fish and fry as they migrate between Lake Manzala and the Mediterranean Sea. Ashtoum El-Gamil represents a critically endangered habitat in both Egypt and the Mediterranean region **(Ahmed *et al*., 2000)**.

This study primarily aimsed to assess the concentrations of potentially harmful elements across multiple environmental compartments—water, sediments, selected aquatic plant species, fish, and bird samples—within the Ashtoum El-Gamil Protectorate.

MATERIALS AND METHODS

1. Study area

The Ashtum El-Gamil Protectorate (AGP) is located 13 km² west of Port Said City, between longitudes 32° 10′ E and latitudes 31° 15′ N, including in its northern part the old and new El-Gamil inlets (Fig. 1). Prime Minister's Decree No. 459/1988 declared it a protected area covering approximately 30 km²; later, Decree No. 2780/1998 expanded its boundaries to around 180 km². The AGP is bordered to the north by the Port Said–Damietta Road, to the east by the Port Said–Ismailia Road, to the south by the Sea of Bahr El-Bashtier in Lake Manzala, and to the west by a line within the Manzala wetland running alongside the Kurumulls Sea and two sea lagoons.

The AGP consists of interconnected basins with distinct water qualities, leading to varied species distributions due to the separation of these basins by a large network of islands. Most islands are covered with native herbaceous plants, while emergent vegetation—primarily *Phragmites australis*, *Typha domingensis*, and *Echinochloa stagnina*—surrounds the islands **(Ayache *et al*., 2009; Bernhardt *et al*., 2011; Mostafa *et al*., 2023)**.

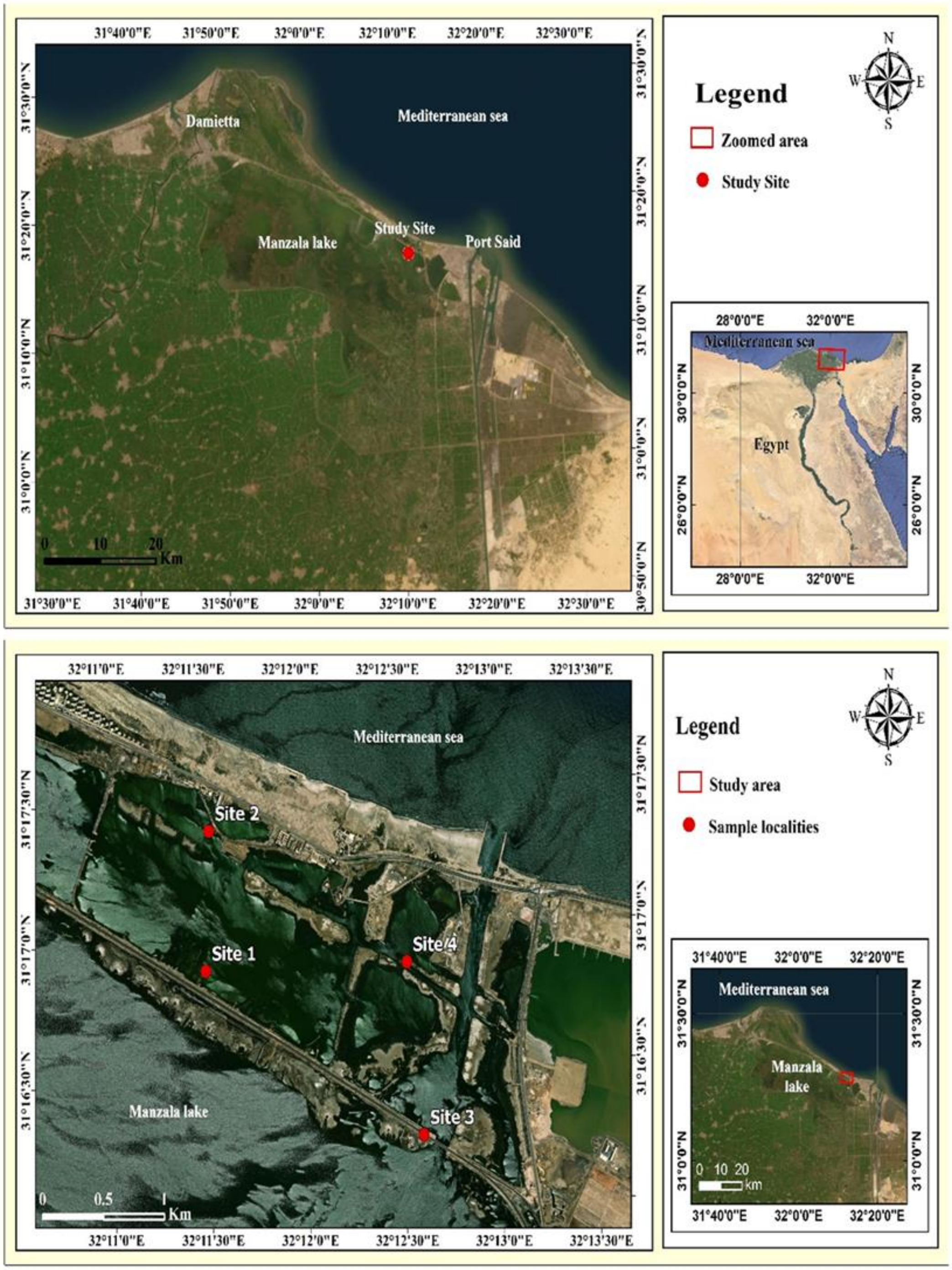

Fig. 1. Location map of sampling sites in Ashtum El-Gamil Protected area, Manzala Wetland, Egypt

2. Collection of samples

Samples of water, sediment, aquatic plants, fish, and a bird species were collected from four selected stations (Fig. 1) during the winter season, specifically in February 2024. The stations were chosen based on the degree of contamination and the presence of the target species. Sediment, water, plant, fish, and bird samples were collected simultaneously from the selected stations (Table 1).

Table 1. Coordinates for the study sites

No.	Latitude	Longitude
Site 1	31°16'53.3	32°11'30.4
Site 2	31°17'23.1	32°11'32.9
Site 3	31°16'15.7	32°12'36.0
Site 4	31°16'52.8	32°12'32.7

2. Sampling and analysis techniques

2.1. Sampling and analysis of water

One liter of water was collected from Sites 2 and 3 in clean, acid-washed polyethylene bottles at approximately 50 cm below the water surface. The samples were filtered using Whatman filter paper to remove suspended particles and debris. To preserve the samples for heavy metal analysis, 0.1% diluted nitric acid was added. The samples were stored at 4 °C until analysis.

Physicochemical parameters were analyzed in the laboratory. pH was measured using a pH meter (Lutron pH-206), while salinity, electrical conductivity (EC), and total dissolved solids (TDS) were measured using a digital portable TDS/conductivity meter (Lutron YK-22CT). Ammonium (NH_3), total ammonium nitrogen (TAN), and selected heavy metals (cadmium, lead, and zinc) were analyzed following the **(APHA, 2017)** standard methods for water examination. Heavy metals were quantified using a flame atomic absorption spectrophotometer (PerkinElmer PinAAcle 500).

2.2. Sampling and analysis of sediment

Sediment samples were collected from Stations 2 and 3 using a plastic shovel washed with deionized water before each sampling to prevent contamination. At each station, a composite sample (n = 3) from a depth profile of 0–30 cm was collected. Samples were transported to the laboratory in clean plastic bags and stored at room temperature until analysis. Heavy metal concentrations were determined using a flame atomic absorption spectrophotometer (PerkinElmer PinAAcle 500).

2.3. Sampling and analysis of plants

Aquatic and halophytic plants were chosen as bioindicators due to their natural capacity to absorb and accumulate pollutants from water and sediments. The selected species included:

- *Typha domingensis* (emergent aquatic plant) and *Eichhornia crassipes* (free-floating aquatic plant) from Station 3.

- *Halocnemum strobilaceum* (halophytic plant) and *Phragmites australis* (emergent aquatic plant) from Station 4.

Roots and rhizomes were rinsed with site water to remove adhered particles, and aboveground parts were harvested. Samples were placed in plastic bags and transported to the laboratory for heavy metal analysis using a flame atomic absorption spectrophotometer (PerkinElmer PinAAcle 500).

2.4. Sampling and analysis of fish

The Nile tilapia (*Oreochromis niloticus*) was selected due to its wide distribution in Egyptian aquatic systems, its role in the human diet, and its capacity to reflect contaminant bioaccumulation in the food web. Fish samples were collected from Stations 3 and 4 within the Ashtum El-Gamil Protectorate. Specimens were transported in iceboxes to the laboratory for chemical analysis. Heavy metals in liver tissue were determined using an inductively coupled plasma–optical emission spectrometer (ICP-OES; Thermo Fisher Scientific iCAP 7400).

2.5. Sampling and analysis of bird

The Cape cormorant (*Phalacrocorax capensis*) was collected from Station 1 within the Ashtum El-Gamil Protectorate. This species, belonging to the family Phalacrocoracidae, is a top predator in the lake's food web, feeding primarily on fish, and is suitable for assessing biomagnification of heavy metals. Sampling occurred during the non-migratory period to ensure contaminant levels reflected local exposure.

P. capensis has been widely used in ecotoxicological research as a bioindicator of aquatic pollution due to its habitat fidelity, feeding ecology, and sensitivity to environmental contaminants. In this study, liver tissues were separated and stored at –20 °C in polyethylene containers until preparation and digestion. Heavy metals were analyzed using a Buck Scientific Accusys 211 atomic absorption spectrophotometer (air/acetylene flame system) following **(Allen *et al*., 1974)**.

3. Assessment of water quality

3.1. Water quality index (WQI)

The WQI integrates multiple physicochemical parameters into a single numerical score to monitor and evaluate water quality changes over time. It was calculated using the formula proposed by **(Tiwari & Manzoor, 1988)**.

$$qi = 100 \text{ x } \left(\frac{Vi}{Si}\right) \quad (1)$$

If the observed value (Vi) and standard value (Si) are exactly same, then equation (1) ensures that quality rating (qi) = 100. So, contamination of water was indicated by the higher qi value. Equation (2) can be utilized to estimate qi and determine WQI corresponding to a particular parameter. Overall, the WQI was:

$$WQI = \sum qi \quad (2)$$

$$AWQI = \sum qi/n \quad (3)$$

Good (from 0.0 to 100), fair (from 100 to 150), poor (from 150 to 200), and extremely poor (above 200) are the four categories into which the average water quality index (AWQI) is categorized.

4. Assessment of heavy metals pollution risk in sediments

4.1. Geoaccumulation index (I_{geo})

Pollution of sediments by metals was assessed using the Index of Geoaccumulation (I_{geo}).
It was calculated using Eq. (4) according to **Muller (1969)**.

$$I_{geo} = \log_2 \left(\frac{Cm}{1.5Cn}\right) \quad (4)$$

Where, C_m is the concentration measured for the metal n in the sediment, C_n is the background value for the metal and factor 1.5 is accounts for potential lithological variance in the background data. Table (2) shows the classification of Geoaccumulation index according to **Muller (1969)**.

Table 2. Classification of Geoaccumulation index **(Muller, 1969)**

Index Class	Igeo Value	Level of Contamination Classification
1	I_{geo} is less than zero.	Not contaminated
2	I_{geo} is greater than 0 and less than or equal to 1	uncontaminated to moderately contaminated
3	I_{geo} is greater than 1 and less than or equal to 2	Slightly to moderately contaminated
4	I_{geo} is greater than 2 and less than or equal to 3	moderately contaminated to strongly contaminated
5	I_{geo} is greater than 3 and less than or equal to 4	Severely contaminated
6	I_{geo} is greater than 4 and less than or equal to 5	strongly contaminated to extremely contaminated
7	I_{geo} is greater than 5	Highly contaminated

4.2. Tomlinson pollution load index (PLI)

Metal enrichment in sediments is estimated using the contamination factor (CF), which compares the value to a baseline. The PLI evaluates the research area's overall pollution grade and sediment toxicity (Eq. 6) **(Tomlinson *et al.*, 1980):**

$$CF = \frac{Cm}{Cn} \quad (5)$$

$$PLI = \sqrt[n]{CF1\ X\ CF2\ \ X\ \ldots\ldots\ldots\ldots\ldots\ CFn} \quad (6)$$

Where, n represents the metal's number, and C_m and C_n are defined as previously. A PLI value of less than 1 indicates no metal pollution, a PLI of 1 suggests minimal pollution, and a PLI greater than 1 signifies a decline in the location's quality **(Tomlinson *et al.*, 1980).**

4.3. Potential ecological risk index (RI)

RI, as established by **Håkanson (1980)**, was utilized to measure the level of ecological risk (Er) (Eq. 4) associated with HMs in sediments. RI evaluates the toxicity of several heavy metals (HMs) to the environment and ecosystems (Eq. 8). CF (Eq. 5) is used to estimate Er (Eq. 7).

$$Er = Tr \times CF \quad (7)$$

$$RI = \sum Er_i \quad (8)$$

Where, E_r and T_r represent for an HM's risk factor and toxic response factor, respectively. The T_r values for Cd, Pb, and Zn were 30, 5, and 1, respectively **(Håkanson, 1980; Cheng & Yap, 2015)**. **Hakanson (1980)** classified ecological risk into five categories: low level, Er < 40; moderate level, 40 ≤ Er < 80; considerable level, 80 ≤ Er < 160; high level, 160 ≤ Er < 320; and extremely high level, Er ≥ 320. Based on the RI, four groups were determined: low ecological risk (RI < 150); moderate ecological risk (150 ≤ RI < 300); significantly high ecological risk (300 ≤ RI < 600); and extremely high ecological risk (RI ≥ 600).

5. Health risk assessment from fish consumption

5.1 Estimated daily intake (EDI)

The estimated daily intake (EDI) for non-carcinogenic effects in both the general population and high fish consumers

The estimated daily intake (EDI) of the tested heavy metals was calculated using Equation (9), as reported by **Chien *et al.* (2002)**.

$$EDI = (EF \times ED \times IR \times MC)/(BW \times AT) \quad (9)$$

The Estimated Daily Intake (EDI) of the analyzed heavy metals was calculated for both the general population and high fish consumers using the following parameters:

- **EDI**: Estimated Daily Intake (mg/kg·day).
- **EF**: Exposure frequency, set at 365 days/year.
- **ED**: Exposure duration for an adult consumer, set at 54 years.
- **IR**: Average daily fish consumption rate for adult Egyptian consumers—64 g/day (0.064 kg/day) for the general population **(FAO, 2014)** and 200 g/day (0.2 kg/day) for high fish consumers **(WorldFish, 2015)**.
- **MC**: Heavy metal concentration in fish samples (mg/kg wet weight).
- **BW**: Average body weight of Egyptian fish consumers aged 16–70 years, estimated at 70 kg.
- **AT (non-carcinogenic effects)**: Average time in days required for the induction of non-carcinogenic effects, calculated as 54 years × 365 days.
- **AT (carcinogenic effects)**: Average time for carcinogenic risk assessment, calculated as 70 years × 365 days **(Bamuwamye *et al*., 2015)**.

5.2. Target hazard quotient (THQ)

Target Hazard Quotients (THQs) were used to evaluate potential non-carcinogenic health risks for both the general population and high fish consumers. THQ is a risk assessment tool that estimates the likelihood of adverse health effects from lifetime exposure to heavy metals through seafood consumption. A THQ value below 1 indicates no significant health risk, while a value above 1 suggests potential non-carcinogenic effects, with the risk increasing proportionally as the THQ rises **(Wang *et al*., 2005)**.

THQ was calculated using the formula **(Chien *et al*., 2002):**

THQ = EDI / RfD (10)

Where EDI, is the estimated daily intake (mg/kg·day); RfD is the oral reference dose, defined as the daily exposure level unlikely to cause adverse health effects over a lifetime.

According to **USEPA (2019)**, the RfD values used are: 0.001, 0.004, and 0.3 for Cd, Pb, and Zn, respectively.

5.3. Target cancer risk (TCR)

Target cancer risk (TCR) is used to estimate the likelihood of cancer occurring due to lifetime exposure to heavy metals through fish consumption. The TCR was calculated using the following formula **(USEPA, 2011; Ullah *et al*., 2017):**

TCR = EDI × CSF (10)

Where, TCR is the target cancer risk; EDI is the estimated daily intake of heavy metals by Egyptian consumers (mg/kg/day); CSF is the cancer slope factor, with values for Cd, Pb, and Zn of 0.38, 0.0085, and 0. If the TCR exceeds 10^{-4}, a carcinogenic health risk is considered present. If the TCR falls between 10^{-6} and 10^{-4}, the risk is considered acceptable **(Ullah *et al.*, 2017)**.

7. Statistical analysis

The results were expressed as the mean ± standard deviation (SD) of three replicates. Using SPSS (ver. 26), a one-way ANOVA was performed on the data. Duncan's multiple ranges were used to perform mean separation at $P<0.05$.

RESULTS AND DISCUSSION

1. Water quality assessment

1.1. Physicochemical parameters

The results of physicochemical parameters in the study areas are summarized in Table (3). pH values showed a highly significant difference ($P \leq 0.000$), ranging from 8.02 at Station 3 to 8.79 at Station 2. These findings are consistent with those reported by **El-Hamid *et al*. (2017)**, who recorded an average pH value of 8.7 in aquatic samples from the Manzala wetland, while **Al-Agroudy and ElMorsi (2022)** reported an average value of 7.

Total dissolved solids (TDS) were 2.3 g/L at Station 3 and 7.51 g/L at Station 2 ($P \leq 0.000$). These results are higher than those reported by **Al-Agroudy and ElMorsi (2022)** at 1.46 g/L but lower than the 16.07 g/L reported by **Ashour *et al*. (2024)**.

Salinity values were 2% at Station 3 and 7.23% at Station 2, also showing a highly significant difference ($P \leq 0.000$). **Ashour *et al*. (2024)** reported a higher salinity of 16.69% for the Manzala wetland, whereas **Goher *et al*. (2017)** reported an average of 5.49%.

Electrical conductivity (EC) values were 3.7 mS/cm at Station 3 and 12.5 mS/cm at Station 2 ($P \leq 0.000$). In comparison, **El-Shazly (2019)** and **Ashour *et al*. (2024)** reported higher mean EC values of 17.8 mS/cm and 23.21 mS/cm, respectively.

These variations in salinity, TDS, and EC may be attributed to differences in evaporation rates, which influence rock weathering and precipitation processes **(Mohamed, 2005; Ashour *et al*., 2024)**.

Ammonia (NH_4) concentrations were 0.06 mg/L at Station 3 and 0.57 mg/L at Station 2, while total ammonium nitrogen (TAN) values were 1.68 mg/L and 2.82 mg/L, respectively ($P \leq 0.000$).

According to the Egyptian Chemical Standards **(ECS, 1994)** under Law No. 4, all measured physicochemical parameters for the Manzala wetland were within permissible limits.

Table 3. Physicochemical parameters of water samples

Parameters	**Unit**	**No.2**	**No.3**	***P* value**
pH		8.79 ± 0.12	8.02 ± 0.01	0.000
Temperature	°C	18.32 ± 0.037	18.3 ± 0.055	0.530
Electrical Conductivity	ms/cm	12.5 ± 0.177	3.7 ± 0.047	0.000
Salinity	%	7.23 ± 0.026	2 ± 0.11	0.000
TDS	g/L	7.51 ± 0.03	2.3 ± 0.085	0.000
NH_3	mg/L	0.57 ± 0.032	0.06 ± 0.0015	0.000
TAN	mg/L	2.82 ± 0.025	1.68 ± 0.0115	0.000
Cd	mg/L	0.022 ± 0.0057	0.003 ± 0.000	0.000
Pb	mg/L	0.01 ± 0.001	0.006 ± 0.000	0.002
Zn	mg/L	0.052 ± 0.0026	0.022 ± 0.002	0.000

Table 4. Comparison between previous studies and the permissible limits for irrigation with the mean of physicochemical parameters of water samples in the present study ± SD

Reference	pH	Temperature (°C)	Salinity %	TDS g/L	EC(ms/cm)	NH_4 mg/L
Elmorsi *et al*., 2017	7.87	14	6.66	6.47	10.3	-
Ashour *et al*., 2024	8.31	-	16.69	16.07	23.21	-
FAO 1994	8.50	< 35	-	2.0	3.00	0-5
ESC (1994)	6-9	5 degree above normal	-	-	-	3
The current study						
Mean ± SD	8.4 ± 0.5	18.31±0.0142	4.615±3.698	4.90 ± 3.68	8.1 ± 6.2225	0.315 ± 0.36
No.2	8.79 ± 0.12	18.32 ± 0.037	7.23 ± 0.026	7.51 ± 0.03	12.5 ± 0.177	0.57 ± 0.032
No.3	8.02 ± 0.01	18.3 ± 0.055	2 ± 0.11	2.3 ± 0.085	3.7 ± 0.047	0.06 ± 0.0015

1.2. Heavy metals in water

Lead concentrations in water samples ranged from 0.006 mg/L at Station 3 to 0.010 mg/L at Station 2. Cadmium values ranged from 0.003 mg/L at Station 3 to 0.022 mg/L at Station 2, while zinc values ranged from 0.020 mg/L at Station 3 to 0.052 mg/L at Station 2 (Tables 3 & 5). **Ashour *et al*. (2024)** reported average lead, zinc, and cadmium concentrations in the Manzala wetland of 0.045, 0.120, and 0.0049 mg/L, respectively. The mean concentrations of the investigated heavy metals in the present study showed a highly significant difference ($P \leq 0.000$).

According to **Ismail and Hettiarachchi (2017)**, zinc concentrations in Manzala wetland aquatic samples ranged from 0 to 0.35 mg/L. In the current results, the mean concentrations of the studied heavy metals were in the order: Cd > Zn > Pb. However, **Khatita *et al*. (2017)** and **Mandour (2021)** reported the order: Zn > Pb > Cd.

All measured heavy metals were within the permissible limits of the Egyptian Chemical Standards **(ECS, 1994)** (Law No. 4), except for cadmium at Station 2, which exceeded the permissible limit.

Table 5. Comparison between mean concentrations (mg/L) of heavy metals in water samples from Ashtum El-Gamil in the current study with previous studies and the permissible limits for irrigation and aquatic life

Reference	Cd	Pb	Zn
Ashour *et al*., 2024	0.0049	0.045	0.12
Ismail and Hettiarachchi (2017)	-	-	0.21
Al-Agroudy and Elmorsi (2022)	0.01	0.695	0.11
Khatita *et al*., 2017	0.033	0.161	0.484
Mandour (2021)	0.00183	0.00568	0.00878
FAO (1994)	0.01	5	2
CCME (2007)	0.001	0.007	0.5
ESC (1994)	0.01	0.01	1
The current study Mean ± SD			
No.2	0.022 ± 0.0057	0.01 ± 0.001	0.052 ± 0.0026
No.3	0.003 ± 0.000	0.006 ± 0.000	0.02 ± 0.002

1.3. Water quality index (WQI)

Overall, the AWQI value was 221.798, which is classified as *seriously poor* (Table 6). These results are consistent with those reported by **El-Hamid *et al*. (2017)** and **Ashour *et al*. (2024)**.

Table 6. WQI & AWQI of Ashtum El- Gamil

	V_i	S_i*	q_i
pH	8.4	8.5	98.8
Temperature	18.31	35	67.8
TDS	4.9	2	245
EC	8.1	3	270
NH_4	0.315	5	6.3
Cd	0.11	0.01	11000
Pb	0.008	5	114.286
Zn	0.036	2	7.2
WQI			1774.398
AWQI			221.798

*FAO, 1994

2. Sediment quality assessment

2.1. Heavy metals in sediment

Manzala wetland, located in the Nile Delta, is the largest naturally occurring saline wetland in the region. However, it faces numerous environmental challenges resulting from human activities. As a primary site for the disposal of industrial and domestic waste in the delta, it requires comprehensive evaluation to assess the effects of metals such as zinc (Zn), cadmium (Cd), and lead (Pb) on its sediments.

This study examined the concentrations of these heavy metals in sediments collected during winter from two selected stations. Cd concentrations exceeded the permissible limit set by the **European Union Standard (2002)**, whereas Pb and Zn concentrations were below the permissible limits. The mean concentrations of the studied heavy metals followed the order: Pb > Cd > Zn, with a highly significant difference ($P \leq 0.000$) across sediments of the Ashtum El-Gamil Protectorate (AGP).

In aquatic systems, Cd is generally more mobile than most heavy metals. Due to its high toxicity and non-degradable bioavailability, Cd has a direct and detrimental impact on ecosystems **(Elhaddad & Redwan, 2022)**. The accumulation of Cd, Pb, and Zn in Manzala wetland sediments has been previously reported by several authors.

Redwan and Elhaddad (2022) recorded mean winter concentrations of 2.1, 20, and 120 mg/kg for Cd, Pb, and Zn, respectively. In contrast, **Gawad (2018)** reported much lower concentrations—0.0264 mg/kg for Cd, 0.244 mg/kg for Pb, and 30.3264 mg/kg for Zn. According to **Redwan and Elhaddad (2022)**, sediment quality reflects the extent to which heavy metals and other organic contaminants may migrate into the water column (Table 7).

Table 7. Comparison between mean concentrations (mg/kg) of heavy metals in sediment samples from Ashtum El-Gamil in the current study with previous studies and the permissible limits

Reference	Cd	Pb	Zn
EU (2002)	3	300	300
CSQGD (2007)	1.4	70	-
Redwan and Elhaddad (2022)	2.1	20	120
Gawad (2018).	0.0264	0.244	30.3264
P value	0.000	0.000	0.000
The current study No. 2 No.3	 10.5 ±0.06 4.04 ±0.05	 13.6 ±0.036 4.09 ±0.01	 1.88 ±0.055 2.94 ±0.02

European Union Standard (2002); **Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health Document (2007)**; SD: standard error.

2.2 Risk assessment of sediment contamination

2.2.1. The geoaccumulation index

The assessed Igeo values indicated that sediments in Ashtum El-Gamil are strongly contaminated with cadmium, whereas the Igeo values for Pb and Zn suggest no pollution (Table 8).

Table 8. I_{geo} and PLI values of different HMs in the sediments of Ashtum El-Gamil

	Cd	Pb	Zn	PLI
Min	3.15	-2.87	-6.24	0.44
Max	4.5	-1.14	-5.6	0.78
Mean	3.8	-2.0	-5.9	0.61

2.2.2. The pollution load index

For each sampling site in the research area, the Pollution Load Index (PLI) was used to describe the overall pollution level of the contaminants **(Cui *et al.*, 2020)**. In Ashtum El-Gamil, PLI values ranged from 0.44 at Site 3 to 0.78 at Site 2, with an average of 0.61. Since all PLI values were below 1, this indicates the absence of overall metal pollution.

2.2.3. Potential ecological risk index

The potential ecological risk index (PERI) for the three heavy metals (Cd, Pb, and Zn) in the study area is presented in Table (9). The mean ecological risk factor (Er) followed the order: Cd > Pb > Zn. Cd exhibited Er values classified as *extremely high risk* (Er ≥ 320), whereas Pb and Zn were classified as *low potential risk*. The overall risk index (RI) ranged from 401.1 (*significantly high ecological risk*) to 1053.4, with a mean value of 727.2, indicating an *extremely high ecological risk* for the area.

Table 9. Ecological risk index values of different HMs in the sediments of Ashtum El-Gamil

	Cd	Pb	Zn	RI
Min	400	3.4	0.02	401.1
Max	1050	1.0225	0.03	1053.4
Mean	725	2.2	0.025	727.2

3. Biological uptake and bioaccumulation

3.1. Heavy metals in plants

Despite the complexity of metabolic processes and interactions between environmental and biological components, traditional biomarkers in many environmental studies—particularly those concerning metal pollution—are the heavy metals accumulated in the cells of aquatic plants **(Kadim & Risjani, 2022; Edo *et al*., 2024)**. Aquatic ecosystems are the primary recipients of heavy metals (HMs) due to the deposition of terrestrial and atmospheric emissions, playing a critical role in self-purification and pollution neutralization **(Marefat *et al*., 2024; Wang *et al*., 2024)**.

The bioaccumulation of HMs by aquatic plants, and their role in the transport and distribution of these metals in wetlands, represents an important aspect of wetland geochemistry **(Xiong *et al*., 2024)**. Numerous studies have screened hydrophyte species capable of accumulating high concentrations of HMs in their tissues for use as bioindicators in assessing heavy metal levels in water and sediments **(El-Amier *et al*., 2020; Abdelaal *et al*., 2021)**.

Macrophytes offer a promising tool for monitoring HM contamination in water because they can effectively accumulate metals through various processes. Metal concentrations in macrophyte tissues often represent existing contamination levels, which may otherwise be diluted under field conditions. While their uptake mechanisms are similar to those of other higher plants, submerged and floating aquatic macrophytes have unique characteristics:

1. They grow directly in water, enabling direct uptake of dissolved metals.
2. They maintain close physical association with specific water bodies, so accumulated metals reflect the contamination status of the surrounding environment over time **(El-Amier *et al*., 2020; Nafea, 2020; Abdelaal *et al*., 2021; Hafez *et al*., 2022)**.

The ability of various plant species to absorb and concentrate different metals (e.g., Cu, Cd, Pb, Zn) has long been recognized **(Goyal *et al*., 2020; Okereafor *et al*., 2020; Zakaria *et al*., 2021)**. In this study, concentrations of Cd, Pb, and Zn in *Phragmites australis*, *Typha domingensis*, *Halocnemum strobilaceum*, and *Eichhornia crassipes* across the sampling area are presented in Table (10), showing a highly significant difference ($P \leq 0.000$).

The highest concentrations of Cd, Pb, and Zn—13.50, 6.45, and 7.63 mg/kg, respectively (order: Cd > Zn > Pb)—were found in *T. domingensis*. For *H. strobilaceum*, concentrations were 9.20, 1.85, and 4.58 mg/kg (Cd > Zn > Pb); for *P.*

australis, 1.54, 2.15, and 2.18 mg/kg (Zn > Pb > Cd); and for *E. crassipes*, 2.00, 3.22, and 4.35 mg/kg (Zn > Pb > Cd).

Compared to WHO permissible limits, cadmium and zinc concentrations exceeded the limits in all species, while lead exceeded the limit in all species except *H. strobilaceum*, where it remained below the maximum allowable level. In *P. australis* and *T. domingensis* from Lake Burullus, **El-Alfy *et al*. (2023)** found metal concentrations in the order Zn > Pb > Cd, whereas **Darwish *et al*. (2023)** reported Pb > Cd > Zn in both species from the New Damietta Drain.

Table 10. Concentrations of heavy metals (mg/kg) in the investigated plant species of Ashtum El-Gamil, HMs concentration values are compared to previous studies and standard levels

Reference	**Cd**	**Pb**	**Zn**
El-Alfy *et al.*, 2023 Burullus Lake *Phragmites australis* *Typha domingensis*	 2.04 5.21	 16.15 19.32	 33.61 35.01
Darwish *et al.*, 2023 New Damietta *P. australis* *T. domingensis*	 11.91 7.51	 43.86 53.78	 - -
WHO (1996)	0.02	2	0.60
P value	0.000	0.000	0.000
The current study *Typha Domingensis* *Halocnemum Strobilaceum* *Phragmites Australis* *Eichhornea Crassipes*	 13.5 ± 0.078 9.2 ± 0.130 1.54 ± 0.094 2 .01± 0.01	 6.45 ± 0.085 1.85 ± 0.029 2.15 ± 0.04 3.22 ± 0.067	 7.63 ± 0.055 4.58 ± 0.045 2.18 ± 0.05 4.35 ± 0.035

3.2. Heavy metals in fish (Nile tilapia)

Contamination of aquatic habitats not only degrades environmental quality but also leads to the contamination of biotic components within ecosystems. Fish are widely recognized as effective bioindicators for assessing the quality of aquatic ecosystems **(Marin *et al*., 2023; Pinna *et al*., 2023; Pérez-Iglesias *et al*., 2023)**. In recent years, research on aquatic ecosystems and biomagnification has increased due to their implications for human health. Contaminants affecting aquatic organisms can directly impact human well-being, as fish and other aquatic species form part of the human diet.

Among these contaminants, heavy metals—particularly cadmium (Cd) and lead (Pb)—are of significant concern. When consumed in excess, these metals can accumulate in the human body and lead to various diseases. Even at low levels, they are not readily eliminated and can cause long-term health problems. Heavy metals enter aquatic environments through both anthropogenic and natural processes **(Moiseenko & Gashkina, 2020; Garai *et al*., 2021; Dahiya, 2022; Singh *et al*., 2022)**.

Toxic substances can be transferred through the fish food chain, resulting in humans, as top predators, ingesting contaminants that are already concentrated or bioaccumulated **(Sonone *et al*., 2020; Mukherjee *et al*., 2021)**. Heavy metals are particularly problematic in aquatic systems due to their high bioaccumulation potential in fish tissues and fluids, posing risks to aquatic life, humans, and other animals. The degree of bioaccumulation is influenced by factors such as fish age, size, diet, environmental conditions, and metabolic processes.

Heavy metal bioaccumulation involves the incorporation of elements from the environment into organisms, leading to increased concentrations and magnification through the food chain. Fish, as higher trophic-level organisms, can accumulate heavy metals beyond safe limits in a process known as biomagnification **(Moiseenko & Gashkina, 2020; Garai *et al*., 2021; Sanou *et al*., 2021; Mukherjee *et al*., 2021; Habib *et al*., 2024)**. Prolonged exposure can cause irreversible effects on human health **(Ali *et al*., 2021; Garai *et al*., 2021; Edo *et al*., 2024)**.

In the present study (Table 11), Cd and Pb were not detected in the liver tissue of Nile tilapia (*Oreochromis niloticus*). The mean concentration of zinc (Zn) was 8.8 mg/kg, which is below the **FAO/WHO (2011)** maximum permissible limit and showed a highly significant difference ($P \geq 0.001$). Zinc naturally occurs in the Earth's crust and can enter aquatic systems via soil erosion and surface runoff **(Oyewo *et al*., 2020; Dahiya, 2022; Singh *et al*., 2023)**. While essential in trace amounts for numerous biological functions, excessive Zn exposure can disrupt metabolic processes, acting as an enzyme inhibitor at high concentrations **(Briffa *et al*., 2020; Kumar *et al*., 2020; Okereafor *et al*., 2020)**.

Zinc plays key roles in enzymatic activity, gene expression, neurotransmission, growth, development, and vitamin A activation. However, excessive intake may cause adverse health effects, including diarrhea, urinary loss, immunodeficiency, copper deficiency, and neurological symptoms. Contaminated fish are a notable source of zinc exposure for humans, as they absorb Zn from both water and diet—through gills, skin, and gastrointestinal tract. Bioaccumulation typically occurs in the liver, gills, muscle, and other tissues **(Chasapis *et al*., 2020; Fu & Xi, 2020; Obasi & Akudinobi, 2020)**.

Table 11. Heavy metals concentrations (mg/kg) in liver of *Oreochromis niloticus* (Nile Tilapia) from Ashtum El-Gamil and comparing the concentration values of HMs with the standard values allowed by different regulations

Reference	**Cd**	**Pb**	**Zn**
EC (2005)	0.05	0.2	-
FAO (2012)	0.05	0.3	50
MAAF (2000)	0.2	2	50
FAO/WHO (2011)	0.5	0.5	40
P value	-	-	0.001
The current study No. 4 No.3 Mean ± SD	 ND ND	 ND ND	 8.5 ± 0.036 9.1 ± 0.04 8.8 ± 0.4

3.3 Human health risk assessment from fish consumption

3.3.1. Non-carcinogenic risk

Most current non-carcinogenic risk assessment methods rely on Target Hazard Quotients (THQs). Recently, many researchers have applied the THQ-based approach, which has proven effective for evaluating the health risks associated with exposure to harmful metals **(Abd-Elghany *et al*., 2024)**. According to **Wang *et al*. (2005)**, fish consumption contaminated with heavy metals does not pose significant non-carcinogenic health risks if the THQ is less than 1. However, when the THQ exceeds 1, the likelihood of chronic non-carcinogenic public health effects increases proportionally with the value.

Table (12) presents the THQ values of heavy metals in Nile tilapia (*Oreochromis niloticus*) for both the general population and high fish consumers. The THQ values for Cd, Pb, and Zn were all below 1 in both consumer groups, indicating no potential for adverse non-carcinogenic health effects from consuming Nile tilapia from the study area. These findings are consistent with those reported by **Sallam *et al*. (2019)** and **Abd-Elghany *et al*. (2024)**.

Table 12. Non-carcinogenic risk assessment using oral reference dose (RfD) values of metals from fish intake and Target Hazard Quotients (THQs)

Heavy metals	RFD (mg/kg/day)	General population	High fish consumers
		THQ	THQ
Cd	0.001	-	-
Pb	0.004	-	-
Zn	0.3	0.027	0.06

3.3.2. Carcinogenic risk

Table (13) presents the Target Cancer Risk (TCR) values for Pb and Cd detected in the Nile tilapia from the Manzala wetland. The results indicate no potential carcinogenic risk from the consumption of these fish for any population group, including both the general population and high fish consumers. These findings are consistent with the conclusions of **Abd-Elghany *et al*. (2024)**.

Table 13. The target cancer risk (TCR) for evaluating carcinogenic risks, cancer slope factors (CSF) values of metals from fish consumption

Heavy metals	CSF (mg/kg/day)	General population	High fish consumers
		TCR	TCR
Cd	0.38	-	-
Pb	0.0085	-	-
Zn	-	-	-

TCR: The target cancer risk

4. Heavy metals in birds

4.1. Heavy metals in cape cormorant (Phalacrocorax capensis)

Ecosystems and their biota can be affected by various potentially toxic elements, including trace elements and heavy metals **(Kolarova & Napiórkowski, 2021)**. Birds inhabiting wetland habitats may ingest these elements through water, soil, and sediments. When sediments are not heavily contaminated, they can serve as a barrier to metal uptake in plant roots. However, wetlands with long-term water flow—often extending across river networks—are key feeding and breeding grounds for birds. Contaminated sediments may act as a pollution source for primary consumers, which in turn exposes birds to heavy metals via direct ingestion of contaminated particles or by consuming prey such as insects, amphipods, fish, and other birds.

In waterbirds, soft tissues such as the liver and kidney are particularly sensitive to heavy metal accumulation, serving as indicators of environmental stress **(Mukherjee *et al*., 2022; Ashraf *et al*., 2023; Aarif *et al*., 2023)**. Such accumulation can lead to:

- Physiological effects, including altered enzyme activities, oxidative damage, and metallothionein induction.
- Immunological or pathological disorders related to the redox activity of metals.
- Reproductive toxicity affecting offspring.
- Behavioral changes, including psychosocial or competitive disorders.
- Reduced survival, due to chronic or sublethal toxicity impacting body condition, hatching success, or parasite resistance.

These pathological and immunosuppressive effects may reduce fledgling survival and pose potential public health risks, as waterbirds can transmit pathogens **(El Shabrawy *et al*., 2021; El-Amier *et al*., 2022; El-Shabrawy *et al*., 2022)**. Trace elements can disrupt biochemical processes by replacing essential elements in enzymes or altering enzyme structures. Many heavy metals are non-essential and highly toxic to cells, even at low concentrations **(Sonone *et al*., 2020; Balali-Mood *et al*., 2021; Witkowska *et al*., 2021)**.

The effects of heavy metal accumulation in bird tissues—including muscle, liver, kidney, and reproductive organs—have been widely studied. Documented impacts include reduced reproductive success, lower hatching rates, embryonic deformities, impaired offspring growth, increased mortality, and changes in organs linked to mating behaviors **(Albayrak & Pekgöz, 2021; Yipel *et al*., 2023; Biswas, 2023)**. These effects have long-term implications for predators, including humans, who consume contaminated biota **(Uddin *et al*., 2021; Vanisree *et al*., 2022)**. Migratory and marsh birds are particularly vulnerable, as they may experience chronic exposure in contaminated habitats **(Biswas, 2023; Zolfaghari, 2023; Kitowski *et al*., 2024)**. Because migratory birds connect ecosystems globally, they can serve as indicators of long-range contaminant transport **(Solgi *et al*., 2020; El-Shabrawy *et al*., 2022; Varagiya *et al*., 2022; Khan *et al*., 2023)**.

Bird susceptibility to heavy metals may be heightened by their high bone calcium content. Under metal stress, birds may demineralize bone to detoxify and remove excess metals. Behavioral studies have shown that heavy metal exposure can alter migratory patterns, with changes more pronounced in individuals or populations with higher tissue metal concentrations **(Seewagen, 2020; Ali *et al*., 2021; Durkalec *et al*., 2022; Varagiya *et al*., 2022)**.

From the present study (Table 14), the concentrations of heavy metals in Cape cormorant (*Phalacrocorax capensis*) liver tissue followed the order: Zn > Cd > Pb. Lead was not detected, while zinc had the highest concentration (5 ppm), remaining below the WHO maximum permissible limit **(WHO, 1998)**. Cadmium concentration was 2.038 ppm, exceeding the permissible limit. In comparison, **Salah-Eldein *et al*. (2012)** reported Zn > Pb > Cd in liver tissues of adult birds (Table 14).

Table 14. Mean concentrations of heavy metals (ppm) in the investigated liver samples and compared by previous studies, in other adult birds.

Reference	**Cd**	**Pb**	**Zn**
Squacco Heron Little Grebe Moorhen Little Tern Purple Gallinule Salah-Eldein *et al*., 2012	0.43 0.39 0.25 0.42 0.17	2.19 3.24 3.30 2.71 3.15	35.62 34.17 47.66 32.38 27.71
WHO (1998)	1	2	100
The current study Mean ± SD	2.038 ± 0.0006	ND	5 ± 0

CONCLUSION

The findings of this study provide a comprehensive assessment of heavy metal distribution and bioaccumulation across multiple environmental compartments in the Ashtum El-Gamil Protectorate. While overall water quality complied with national standards, elevated cadmium levels at one site highlight the need for localized source identification and control. Sediments acted as a major sink for heavy metals—particularly lead and cadmium—posing potential long-term ecological risks. Aquatic plants displayed species-specific accumulation patterns, with *Typha domingensis* and *Halocnemum strobilaceum* exhibiting a greater tendency to accumulate cadmium, suggesting their potential as bioindicators or for phytoremediation applications.

Fish samples contained metal concentrations within safe limits, indicating limited transfer to lower trophic levels. However, cadmium levels exceeding WHO limits in the liver of the Cape cormorant point to possible biomagnification and ecological stress at higher trophic levels. These results emphasize the need for ongoing environmental monitoring—especially of top predators—and support the implementation of targeted management strategies to mitigate pollution sources. Recent dredging activities in the lake may contribute positively to habitat recovery, but post-restoration monitoring is essential to evaluate their long-term ecological benefits.

Acknowledgements

Thanks to Prof. Taha Mohamed El-katony, Professor of Plant Physiology, Botany and Microbiology Department, Faculty of Science, Damietta University, for help with statistical data analysis.

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