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Water Feature and Heavy Metal Pollution Indices in Lake Qarun, Fayoum, Egypt

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ABSTRACT

Lake Qarun, a significant water body in Egypt, receives agricultural drainage from the El Fayoum Governorate via several drains, with El-Wadi and El-Bats drains being the primary sources. This study assessed the current water quality of Lake Qarun, heavy metal (HM) concentrations, and pollution indices in both water and the Nile tilapia (*Oreochromis niloticus*), and the associated human health risks from fish consumption. Based on the Canadian Water Quality Index (CWQI = 47) and the Oregon Water Quality Index (OWQI = 16-38), water quality assessments categorized Lake Qarun as marginal and very poor, respectively. The trophic state index (TSI) ranged from 62.16 to 85.6 throughout the year, indicating poor water quality. Conversely, the Aquatic Toxicity Index suggested that the water remained suitable for fish survival. HM concentrations in the water followed the sequence Fe>Al>Mn>Zn> Pb>Cr> Cu>Ni >Co>Cd. Pollution index (PI) revealed slight pollution by Co, Mn, and Pb in the eastern sector, while Cu exhibited intense pollution near the El-Bats Drain. The HM Pollution Index (HPI) indicated high overall HM pollution in Lake Qarun, potentially posing adverse effects on aquatic organisms. Bioaccumulation factors for HMs in the edible tissue of *Oreochromis niloticus* were in the sequence of Cd>Ni >Cu> Co > Zn > Mn >Pb> Al > Cr > Fe. Despite individual metal target hazard quotients (THQ) being below the non-hazardous limit (THQ < 1), the Total Hazard Index (HI > 1) revealed a potential health risk to *Oreochromis niloticus* consumers from the combined effect of heavy metals. This risk was relatively higher in the eastern sector (HI = 1.275) compared to the western sector (HI = 1.148).

INTRODUCTION

Water is the primary foundation of life for all living things. It is a component of nearly every production process healthy humans use in healthy ecosystems for transportation, energy, manufacturing, and agriculture **(Ghanem *et al.*, 2016)**. Lakes are key elements of the global water supply, and reservoirs supply water for drinking, irrigation, electricity production, and habitat for countless plant and animal species **(Goher *et al.*, 2017)**. The world's lakes are home to the most prolific, varied, dynamic, and fertile ecosystems. The existence of aquatic animals, including fish, is seriously threatened by both organic and inorganic pollution of the water environment **(Goher *et al.*, 2017)**.

One of the most significant threats affecting Egypt is water pollution with harmful compounds like heavy metals (HMs) because of urban, industrial, and agricultural waste distribution or disposal **(Abdel-Mohsien & Mahmoud 2015; Alm-Eldeen *et al.*, 2018)**. One of Egypt's biggest and oldest lakes is Lake Qarun. It's a closed water system with shallow depths (2–5 meters), stretching across 230km^2. It serves as a holding area for El-Fayoum province's agricultural drainage water **(Abdel Wahed, 2015)**. The sources of urban and agricultural wastewater of the lake are mainly the El-Bats and El-Wadi drains, in addition to ten inferior drains that are emptied into the lake by several hydraulic pumps **(Shadrin *et al.*, 2016; Salaah *et al.*, 2022)**.

Environmental strain on Lake Qarun results in a variety of problems for the aquatic life and ecology of the lake **(Shalloof, 2020; Abd-El-Baky, 2022)**. These problems include huge volumes of irrigation and sewage water, a lack of freshwater intake, an increasing rate of evaporation, and wind-blown sands that attack it from the north and northwest. In addition to improving aquatic life and water quality, lake restorations are usually done for recreational and aesthetic reasons **(Abd-El-Baky, 2022)**.

Qarun Lake's salinity increased significantly during the past century **(AbdEllah, 2009)**. The salinity rose from about 8% in 1905 to 34.5% in 1987. The lake's subtropical environment, which results in high temperatures and seasonal variations in the evaporation rate, and the wastewater are the reasons for the increase in salinity **(Anwar *et al.*, 2001)**. In addition, these serve as many sources of pollutants that place strain on the lake's surface water quality **(Zhao *et al.*, 2012; Wu *et al.*, 2018)**. Wastes, salts, and nutrients abound in such water, with the potential to build up and contaminate the aquatic ecosystem **(Khalaf-Allah, 2014; Shalloof, 2020)**. The dumping of agricultural and urban sewage wastes into Lake Qarun leads to significant issues with the quality of water. Since water conditions are paramount for the survival and quality of fish, consistent monitoring of physical and chemical attributes is essential. Supplying optimal environmental conditions ensures both healthy fish populations and successful aquaculture ventures **(Onada *et al.*, 2015)**. To quickly understand the state of water in various bodies, the water quality index (WQI), a numerical tool, is used. It offers a clear picture of river, lake, and stream conditions **(Kükrer & Mutlu, 2019)**.

Fayoum province releases annually about 500 million cubic meter of untreated waste effluents into Qarun Lake **(El-Zeiny *et al.*, 2019)**. In addition to its significance as a natural drainage system for El-Fayoum region, Lake Qarun is a significant location for tourism, migrating birds, salt production, and fishing during cold season **(Barakat *et al.*, 2017; Saleh *et al.*, 2021)**. Thus, by Presidential Decree No. 943/1989, the Qarun region was designated as a nature reserve in compliance with Law No. 102 of 1983 **(El Naby *et al.*, 2018)**. Qarun Lake fisheries output dropped over the past ten years, and the lake's future was uncertain for a variety of reasons, many of which were not well understood **(Abdelmageed *et al.*, 2022)**. **Mehanna**

(2020) investigated the effects of isopod parasites on Lake Qarun's fisheries resources. She came to the conclusion that excessive pollution, poor management practices, and illogical exploitation were the main causes of Lake Qarun's declining fish yield.

The most persistent pollutants that accumulate in the biota and make their way into the food chain are trace metals, which are among the most significant contaminants and pose a major health risk to humans **(Elhdad, 2019)**. They also get into the aquatic ecosystem through erosion, air deposition, and human activity. Additionally, mining, home sewage, and industrial effluents have all contributed to a rise in heavy metals **(Bahnasawy *et al.*, 2011)**. Because they bioaccumulate, heavy metals are extremely harmful to humans and marine life, even at very low doses. These are inorganic, nondegradable substances that are hard to digest and have a tendency to build up in organisms' bodies over time **(Batvari & Saravanan, 2020)**. Therefore, even a trace amount of them in fish could pose a major risk to consumers' health **(Bat *et al.*, 2020)**. Under certain environmental conditions, heavy metals can accumulate to toxic levels, posing significant risks to both ecological systems and human health **(Wongsasuluk *et al.*, 2014)**.

This study aimed to conduct a comprehensive assessment of the current environmental status of Lake Qarun in Egypt by analyzing water quality, identifying the impact of agricultural and different wastes on the lake, assessing HMs pollution levels in water and tissues of the Nile tilapia fish (*Oreochromis niloticus*), and evaluating the potential health risks to humans from consuming these fish. Therefore, the significance of this study lies in providing accurate scientific information about the environmental status of Lake Qarun, which helps make informed decisions for water resource management, protecting human health, and conserving fish health in the lake.

MATERIALS AND METHODS

Study area and sampling

Geographically, Lake Qarun represents a terminal saline lake within the northern sector of Egypt's Western Desert. Its location is defined by its placement within the Fayum Depression's nadir, spanning the coordinates 29° 24′ to 29° 33′ north latitude and 30° 24′ to 30° 49′ east longitude with about 230km^2 **(Abd-El-Baky, 2022)**. Two main drains carry drainage water from the east (El-Bats Drain) and the south (El-Wadi Drain), and several minor drains discharge the wastewater along the southern border of the lake. In 2023, ten subsurface water samples were taken periodically to cover the area being studied next to the El-Bats and El-Wadi main drains (Fig. 1). Table (S1) (in the supplementary data) provides information about surface water sampling locations, including their latitude and longitude.

Water sampling

The seasonal subsurface water samples were taken using a 2L Ruttner water sampler. For further analysis in the lab, water samples were preserved by being placed in 2-liter polyethylene bottles and kept at a low temperature within a cooling box. Samples for dissolved oxygen (DO) and biochemical oxygen demand (BOD) were collected in 300mL specialized stoppered glass bottles. One milliliter of 40% $MnSO_4$ and one milliliter of alkaline KI solution were added to the dissolved oxygen samples, and they were thoroughly mixed. Aluminum foil was placed over the bottles containing the BOD samples to reflect light, following the American Public Health Association's guidelines **(APHA, 2017)**. Water samples for heavy metals were collected and kept in clean, 1-L plastic bottles. The samples were then preserved with five milliliters of Conc HNO_3 to lower the pH to less than two. This prevented the majority of bacteria from growing, stopped oxidation reactions, and prevented the heavy metals from precipitating or adhering to the container surface while being transported. After that, the samples were kept in a refrigerator.

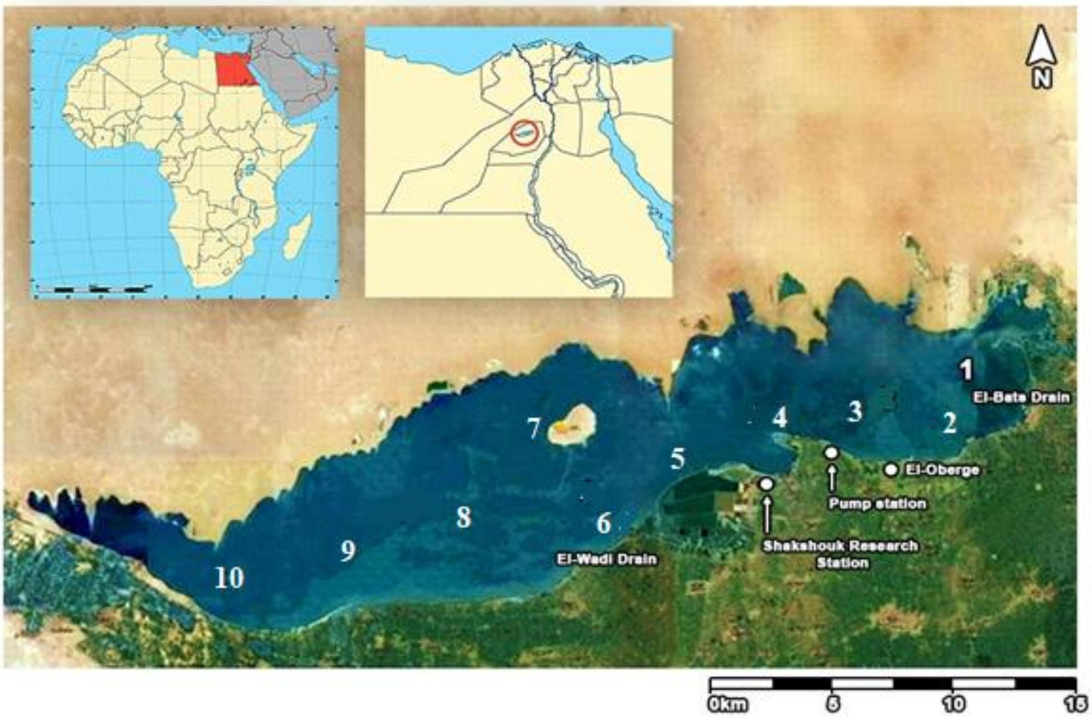

Fig. 1. Map of Qarun Lake showing the sampling locations

Fish sampling

Using nets deployed by local fishers, in winter 2023, 70 Nile tilapia fish (*Oreochromis niloticus*) were obtained from two distinct locations within Lake Qarun: sites 2 and 8, which correspond to the eastern and western regions, respectively, weighing an average of 150-190 ± 33.20g and an average length of 14-22 ± 3.13cm, and then transported to the laboratory in an icebox. Upon collection, each fish specimen underwent dissection to facilitate the examination of its muscular tissue, reproductive organs, kidney, gills, and liver. Between the pelvic and dorsal fins on the left side of the fish, muscle tissue was removed. After rinsing with deionized water, all tissues were put in vials with labels, acid-washed, and frozen at -20°C. To prepare the tissues for biochemical analysis, they were processed in phosphate-buffered saline (pH 7.4) using homogenization, followed by centrifugation at 4000rpm for 15 minutes. After being taken out, the supernatant was frozen pending analysis.

Procedures

Water analysis

Direct, on-site measurements of water transparency, pH, electrical conductivity (EC), and temperature were conducted using a Secchi disk and a Hydro-lab model Orion Research Ion Analyzer 399A, respectively. Generally, the water analysis techniques were carried out in accordance with **APHA (2017)**. A specific volume of a water sample was filtered through GF/C filters and was then evaporated at 180°C to estimate the salinity. By passing a known sample volume through a GF/C filter and drying it at 105°C, the total suspended solids (TSS) were determined. The modified Winkler method was used to determine the amount of dissolved oxygen (DO). The 5-day approach was used to determine the biochemical oxygen demand (BOD). The potassium dichromate method was used to calculate the chemical oxygen demand (COD). Colorimetric techniques were used to measure the concentrations of nutrient, by which resulted in the formation of reddish-purple azo dye with nitrite (NO_2^- -N), cadmium reduction with nitrate (NO_3^--N), phenate with ammonia (NH_4^+-N), ascorbic acid molybdate with orthophosphate (PO_4^{3-}-P), total phosphorus (TP), and molybdosilicate methods with reactive silicate (SiO_4^{-4}-Si), respectively.

HM in water and fish

For HM analysis, preserved water samples were prepared by nitric acid (HNO_3) digestion, adhering to the guidelines specified in **APHA (2017)**. Fish tissues of the Nile Tilapia (*O. niloticus*) were digested according to **FAO/SIDA (1983)**. Inductively Coupled Plasma Emission Spectrometry (ICP-ES), equipped with an Ultra Sonic Nebulizer (USN) on a Perkin Elmer Optima 7000 instrument, was employed to quantify the total concentrations of cadmium (Cd), copper (Cu), cobalt (Co), chromium (Cr), aluminum (Al), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) in digested samples of water and fish organs. The details of HMs sample preparation and analysis of water and fish tissue are found in the supplementary file (ST1 and ST2).

Bioaccumulation factor (BAF)

The following formula was used to calculate heavy metal's bioaccumulation factor (BAF) in fish tissues:

$$BAF = M_t / M_{wa}$$ **(El-Khatib *et al.*, 2020)**

Where, M_t and M_w are the concentrations of HM in different tissues (µg/g wet weight), and water (µg/l), respectivey. BAF values of HM are categorized according to **Olayinka-Olagunju *et al.* (2021)**, where BAF < 1000 indicates no chance of bioaccumulation, 5000 > BAF > 1000 indicates bioaccumulative metal, and BAF > 5000 indicates extremely bioaccumulative metal.

Statistics

Using Excel-Stat software (2019), the significance of variance in the collected data across different seasons and sites was analyzed using a one-way ANOVA test. Additionally, Pearson correlation coefficients (r) and standard deviations were calculated.

Water quality indices

The adequacy of the water in Qarun Lake for the usage of aquatic life was assessed using four integrated water quality indices including the Trophic State Index (TSI), Oregon Water Quality Index (OWQI), Canadian Water Quality Index, and Aquatic Toxicity Index (ATI) according to **Carlson and Simpson (1996)**, **Sarkar and Abbasi (2006)**, **(CCME, 2021)** and **Gupta and Gupta (2021)**, respectively. The defiles of these indices are found in the supplementary data (ST3 and Tables S2- S5).

Metal pollution indices

Two HM indices were computed to assess the HM pollution degree in the water of Qarun Lake. The first one is the Pollution Index (PI), designed to assess the impact of individual metals, which provides a classification system consisting of five distinct categories (Table S6 in the supplementary data) **(Caerio *et al.*, 2005)**. While the second index is the Heavy Metal Pollution Index (HPI), which evaluates the collective impact of heavy metals on water, indicating both the degree of pollution and the water's suitability for aquatic organisms **(Hassouna *et al.*, 2019)**. The details of the metal indices are presented in the supplementary data (ST4).

Target hazard quotient (THQ) and hazard index (HI)

The Target Hazard Quotient (THQ) serves as an indicator of potential non-carcinogenic health effects, derived from the ratio of estimated pollutant exposure to a reference dose **(Kortei *et al.*, 2020)**. It is crucial to understand that the THQ is not a direct measure of risk, but rather a metric of concern. Individual heavy metal THQs were calculated following the methodology outlined by **USEPA (2013)**. The Hazard Index (HI) for residents of Fayoum Governorate of Egypt, who consume the Nile tilapia (*O. niloticus*) from Qarun Lake, was obtained using equations according to **USEPA (2013)**. The details of the calculation are presented in the supplementary data (ST5). A threshold value of unity (1) is established for both (THQ) and (HI). Values below this threshold suggest negligible risk to consumers, whereas values exceeding 1 may indicate a potential for adverse health effects in humans.

RESULTS AND DISCUSSION

Physical characteristics

Water temperature serves as a pivotal control parameter within aquatic ecosystems. It ranged between 14.09 – 23.92°C throughout the year, showing a temporally difference ($P < 0.01$). Due to the lake's short depth (around 4m on average), no distinct thermal stratification has been observed, which is appropriate for aquatic life, including fish (8–28°C), and it is thought to be homeothermic in nature **(Al-Afify *et al.*, 2019)**.

Qarun Lake typically exhibits water turbidity, primarily caused by the negative impact of the discharged wastewater **(Khalil *et al.*, 2017)**, with a temporal and spatial difference (*P*< 0.01) of TSS that fluctuated in the range of 38.19 - 103.0mg/ l. The maximum TSS was found opposite to El-Wadi drain at station 6 in the winter, while the minimum of 38.19mg/ L was observed at station 10 in spring. In an opposite manner, station 1, that is opposite to the El-Bats drain, showed the minimum transparency values, whereas the western part of the lake that is far from the drains had the maximum transparency values. Transparency is negatively correlated (*P*< 0.01) with (TSS) (r = -0.62). Salinity of Qarun Lake water showed a wide range (13.12–43.38g/ l), showing a notable variance between the sites (*P*< 0.01). Sites closed to the drains exhibited the lowest values, while the highest salinity was observed at stations 7-10. These data corroborate the results documented by **Abd El-Aal *et al.* (2019)**. The presence of anions like sulfate and chloride as well as cations like sodium, calcium, and magnesium indicates salinity **(Rani *et al.*, 2012)**, robust positive correlation (r ranging from 0.7 to 0.99, n=40, *P*< 0.01) was found between salinity and both cations and anions.

Chemical characteristics

The pH levels, a key factor in aquatic life **(El Sayed *et al.*, 2022)**, were found to be alkaline, suggesting increased photosynthetic activity by planktonic algae **(Hegab, 2025)**. Demonstrating significant temporal and spatial variation (*P*< 0.01), pH ranged from 7.79 to 8.96, all within the acceptable range (6-9), which is ideal for increased fish production **(Khalefa *et al.*, 2021)**. Station (1) in front of El Bats Drain entrance had comparatively lower pH readings because of wastewater discharge that was heavily loaded with different pollutants **(Ahmed, 2012)**. Its worth mentioning that pH values were positively correlated (r = 0.71) with DO. The dynamic interplay between algal photosynthesis, respiration within the aquatic environment, shifts in water temperature, and the breakdown of organic material through oxidation dictates the changes seen in pH and DO **(Shetaia *et al.*, 2020)**.

The water in Qarun Lake was well-oxygenated during the colder seasons (winter and autumn), with dissolved oxygen levels reaching up to 11.7mg/ L. This increase is attributed to phytoplankton blooms **(Konsowa, 2007)**, the action of prevailing winds—considered a natural source of oxygen in aquatic environments—and the lower water temperatures, which enhance the atmospheric solubility of oxygen gas **(Goher *et al.*, 2017)**. A substantial negative correlation between DO/temperature (r = -0.35) supports this. During the summer, the lowest levels of DO were observed at station (6), which could potentially be attributed to the large amount of wastewater from El Wadi drain with a high load of organic matter. Also, the negative correlation between oxygen and most nutrients (r = -0.67 to -0.72, n=40, *P*< 0.01) is due to the effect of drains and wastewater, loaded with huge amounts of nutrients on reducing the oxygen concentration in the water. Additionally, DO is negatively correlated with metals such as Fe (r = -0.57), Mn (r = -0.66), Cu (r = -0.58), Ni (r = -0.46), Co (r=-0.58), Al (r = -0.56), Cd (r = -0.51), and Pb (r = -0.45), which shows how high dissolved oxygen contributes to metal settling in the sediment; These observations are in agreement with **Goher *et al.* (2018)**. BOD and COD varied from 7.0 to 13.38mg/ l and 27.7 to 38.67mg/ l. COD showed a high spatially significant variation (P< 0.01), while BOD showed a high temporally and spatially significant variation (P< 0.01). The highest COD and BOD values were observed in the hot period, which was consistent with those found by **Abdel Gawad *et al.* (2022)**. This might have to do with the temperature elevation and activity of bacteria, which accelerate the breakdown of organic materials **(El-Shabrawy *et al.*, 2015)**.

Nutrient salts

Nutrients have a significant impact on the productivity of aquatic ecosystems that sustain the food chain for fish, phytoplankton, and zooplankton **(Hassouna *et al.*, 2018)**. Nitrite, nitrate, ammonia, total nitrogen orthophosphate, total phosphorus, and silicate fluctuated in the range of 4.4 – 261.06µg/ L, 0.009 – 0.777mg/ L, 0.105 – 4.519mg/ L, 0.68 – 9.52mg/ L, 25.3 – 177.1µg/ L, 51.7 – 322.3µg/ L and 4.68 – 12.22mg/ L, respectively. The observed nitrate concentrations surpassed nitrite levels, a result of the swift transformation of NO_2^- ions into NO_3^- ions facilitated by nitrifying bacteria **(Goher *et al.*, 2017)**.

Stations (1) and (6) (the entrance of both El Bats and El Wadi drains wastewater) represent the highest nutrient (nitrite, ammonia, nitrate, orthophosphate, and total phosphorus) values; this agrees with the findings obtained by **Haroon *et al.* (2018)**. According to **Saad *et al.* (2011)**, runoff from agricultural areas, particularly those that are intensively farmed and heavily fertilized with synthetic fertilizers and urban wastewater, causes nutrient contents in water. Nitrites is positively correlated with almost nutrients and heavy metals (P< 0.01), e.g. Fe (r = 0.62), Zn (r = 0.48), Cr (r=0.53), Co (r=0.50), Cd (r=0.49), Pb (r= 0.49), Al (r = 0.69), (P< 0.05) with Cu (r = 0.32, P< 0.05), Mn (r=0.40, P< 0.05), Ni (r = 0.40, P< 0.05), indicating their common origin (agricultural pesticides) **(Goher *et al.*, 2017)**. Orthophosphate and TP showed a high spatial variance (P< 0.01), while silicate showed a highly temporal variance (P< 0.01). The descriptive data of the water analyses of Qarun Lake are illustrated in Table (1).

Table 1. Physico-chemical characteristics of Qarun Lake water

	Winter	Spring	Summer	Autumn	Range	Mean ± SD
Temp (°C)	**13.5-14.7**	**21.9-28.55**	**26.12-29.3**	**20.27-23.39**	**13.5-29.3**	**22.47±5.43$^{b, c}$**
Transparency (cm)	**10-60**	**15-70**	**5-70**	**20-80**	**5-80**	**40.38±17.30^{a}**
Salinity (TDS) (g/l)	**18.42-42.47**	**13.12-41.65**	**22.2-43.38**	**21.56-43.55**	**13.12-43.55**	**38.38±7.30^{a}**
TSS (mg/l)	**51-103**	**38.19-76.22**	**41.28-91.38**	30.16-66.89	**30.16-103**	**57.55±18.9$^{a, b}$**
pH	**8.13-8.96**	**7.9-8.83**	**7.79-8.56**	7.82-8.64	**7.79-8.96**	**8.40±0.30$^{a, b}$**
DO (mg/l)	**4.23-8.14**	**1.55-11.7**	**0.58-4.8**	**2.26-8.34**	**0.58-11.7**	**5.01±2.54^{a}**
BOD (mg/l)	**7-12.58**	**7.1-12.28**	**9.23-13.38**	**6.62-11.42**	**6.62-13.38**	**9.49±1.97$^{a, b}$**
COD (mg/l)	**30.12-34.82**	**27.07-38.67**	**29.35-36.07**	**25.76-34.4**	**25.76-38.67**	**31.41±2.74^{a}**
CO_3 (mg/l)	**12-18.2**	**4.2-18.6**	**4.8-16**	**6.2-16**	**4.2-18.6**	**13.79±3.81$^{a, b}$**
HCO_3 (mg/l)	**139.89-256.2**	**237.9-296.5**	**224.9-325.7**	**292.4-414.4**	**139.9-414.4**	**263.8±61.9$^{a, b}$**

Cl (g/l)	**5.67-13.92**	**4.42-13.44**	**7.03-13.97**	**6.94-15.3**	**4.42-15.3**	**12.68±2.52**[a]
SO_4 (g/l)	**5.53-12.64**	**4.02-12.21**	**6.74-12.7**	**6.31-13.89**	**4.02-13.89**	**11.56±2.24**[a]
Ca (g/l)	**0.16-0.50**	**0.13-0.51**	**0.20-0.51**	**0.19-0.53**	**0.13-0.53**	**0.44±0.10**[a]
Mg (g/l)	**1.26-2.70**	**1.04-2.64**	**1.21-2.75**	**1.26-2.85**	**1.04-2.85**	**2.26±0.50**[a, b]
Na (g/l)	**5.44-12.17**	**3.75-12.03**	**6.38-12.64**	**6.28-12.72**	**3.75-12.72**	**11.15±2.08**[a]
K (g/l)	**0.13-0.37**	**0.09-0.35**	**0.15-0.37**	**0.17-.37**	**0.09-0.37**	**0.32±0.07**[a]
NO_2 (μg/L)	**9.38-192.8**	**4.4-64.8**	**10.55-261.1**	**20.27-23.39**	**4.4-261.1**	**36.53±57.5**[c]
NO_3 (mg/l)	**0.04-0.777**	**0.035-0.684**	**0.009-0.36**	**0.052-0.498**	**0.009-0.777**	**0.16±0.19**
NH_4 (mg/l)	**0.105-4.519**	**0.206-2.332**	**0.23-3.286**	**0.274-2.856**	**0.105-4.519**	**0.96±1.09**[a]
TN (mg/l)	**0.68-9.52**	**0.82-4.07**	**0.69-5.86**	**0.54-6.24**	**0.54-9.52**	**2.01±1.95**[a]
SiO_2 (mg/l)	**10.73-12.22**	**4.68-10.39**	**6.55-12.10**	**9.5-14.31**	**4.68-14.31**	**9.99±2.87**[b]
PO_4 (μg/L)	**25.3-177.1**	**31.9-106.7**	**34.1-130.9**	**38.5-97.9**	**25.3-177.1**	**60.75±32.4**[a]
TP(μg/L)	**51.7-322.3**	**79.2-202.4**	**112.2-191.4**	**61.6-162.8**	**51.7-322.3**	**112.3±50.8**[a, d]

Letter symbols represent significant difference: a: $P < 0.01$ spatial variations, b: $P<0.01$ temporal variations, c: $P < 0.05$ spatial variations, d: $P<0.05$ temporal variations.

It is worth noting that, the El-Bats and El-Wadi drains exhibited higher turbidity, with water transparency reduced to 5-10cm. Total dissolved solids (TDS) levels in these drains were measured between 1.92-2.09g/ l (El-Bats) and 1.64-2.49g/ l (El-Wadi) (Table 2), significantly lower than those of the lake water. The TSS levels in the El-Bats and El-Wadi drains varied between 22.8-105 and 23.17-109mg/ l, respectively, exceeding those of the lake water. Nitrite, nitrate, ammonia, total nitrogen orthophosphate, total phosphorus and silicate in El-Bats fluctuated in the range of 297.7-598.3μg/ L, 0.484-1.560mg/ L, 4.67-22.8mg/ L, 8.37-11.75mg/ L, 133.1-275μg/ L, 214.5-383.9μg/ L and 7.53-13.21mg/ L, respectively, and in El-Wadi drains water fluctuated between 359-504μg/ L, 1.004-1.256mg/ L, 2.902-4.837mg/ L, 6.51-9.63mg/ L, 105.6-222.2mg/ L, 194.7-391.6mg/ L and 8.44-12.31mg/ L, respectively.

Table 2. Water quality criteria of Qarun Lake drains

	Bats Drain		**Wadi Drain**	
	Range	**Mean ± SD**	**Range**	**Mean ± SD**
Temp (°C)	**14.09-23.92**	**20.43±4.41**	**14.26-23.17**	**20.24±4.2**
Transparency (cm)	**5-10**	**7.5±2.89**	**5-10**	**8.75±2.5**
Salinity (TDS) (g/l)	**1.92-2.09**	**2.02±0.10**	**1.64-2.49**	**2.13±0.37**
TSS (mg/l)	**22.8-105**	**76.21±36.46**	**23.17-109**	**70.20±35.39**
pH	**7.51-7.8**	**7.65±0.12**	**7.75-7.9**	**7.84±0.07**
DO (mg/l)	**1.08-3.56**	**2.04±1.06**	**1.18-3.71**	**2.46±1.13**
BOD (mg/l)	**12.14-13.88**	**12.95±0.73**	**10.83-12.76**	**12.0±0.68**
COD (mg/l)	**35.24-41.28**	**2.69±2.74**	**34.58-40.35**	**2.59±0.37**
CO_3 (mg/l)	**6-21**	**12±6.48**	**5-24**	**13.5±7.94**
HCO_3 (mg/l)	**280.6-341.6**	**305±27.73**	**292.8-433.1**	**350±63.1**
Cl (g/l)	**0.59-0.84**	**0.67±0.12**	**0.68-1.14**	**0.96±0.20**
SO_4 (g/l)	**0.73-0.91**	**0.84±0.08**	**0.63-0.71**	**0.68±0.03**
Ca (g/l)	**0.04-0.05**	**0.05±0.00**	**0.05-0.06**	**0.05±0.00**
Mg (g/l)	**0.11-0.12**	**0.12±0.01**	**0.13-0.14**	**0.13±0.00**
Na (g/l)	**0.80-0.88**	**0.83±0.04**	**0.82-0.89**	**0.86±0.03**
K (g/l)	**0.01-0.04**	**0.03±0.01**	**0.01-0.04**	**0.03±0.01**
NO_2 (μg/L)	**297.7-598.3**	**425±126.3**	**359-504**	**414±60.8**

NO_3 (mg/l)	**0.484-1.560**	**1.104±0.47**	**1.004-1.256**	**1.063±0.21**
NH_4 (mg/l)	**4.67-22.8**	**9.859±8.66**	**2.902-4.837**	**3.8±0.79**
TN (mg/l)	**8.37-11.75**	**9.5±1.52**	**6.51-9.63**	**7.5±1.47**
SIO_2 (mg/l)	**7.53-13.21**	**9.36±3.8**	**8.44-12.31**	**11.27±1.9**
PO_4 (μg/L)	**133.1-275**	**224.57-63**	**105.6-222.2**	**155.24-49.87**
TP (μg/L)	**214.5-383.9**	**329.45±79**	**194.7-391.6**	**270±106**

The primary processes regulating the water chemistry in Qarun Lake are the dissolution of soluble salts and ongoing evapo-concentration. The dry and hot climate environments dominated the area, reinforcing the trend of evaporation toward the lake **(Abdel Wahed *et al.*, 2015)**. Thus, under arid conditions, progressive evaporation of drainage water entering Lake Qarun has led to a concentration of sodium, magnesium, chloride, and sulfate ions, exceeding levels in transitional and upstream zones, thereby causing a marked increase in salinity. Consequently, this shift has profoundly altered the lake's water chemistry. Major cations (Na^+, K^+, $Ca^{2+,}$ and Mg^{2+}) of lake water were within the spans of 3.75-12.72, 0.09 – 0.37, 0.13 – 0.53, and 1.04 – 2.85g/ l, respectively.

Within Lake Qarun's waters, sodium emerged as the principal cation, with the hierarchical order of cation abundance being $Na^+ > Mg^{2+} > Ca^{2+} > K^+$. Major anions ($CO_3^{-2}$, HCO_3^-, Cl^{--} and SO_4^{2--}) of Lake water were within the spans of 4.2 – 18.6, 139.89 - 414.39, 4.42 - 15.3 and 4.02- 13.89g/ l, respectively. Conversely, chloride ions were the most abundant anions in the water, with the anion sequence following the order $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{-2}$. These findings align with those reported by **Abou El-Gheit and Abdo (2012)**. It is quite clear that the concentration of SO_4^{2-} in Lake Qarun was much higher level in comparison to seawater, while the chloride level was higher in seawater (Table 3). Also, Na_2SO_4 and $CaCO_3$ salt levels are disappearing in seawater contrast to Qarun Lake, while $MgCl_2$ is disappearing in Qarun Lake comparison to seawater. This difference is due to the nature of the wastewater that forms Lake Qarun, which also makes it fluctuate annually, with a noticeable increase over time.

Table 3. Ionic composition of Qarun water compared to standard seawater

Ions	**Qarun (40‰)**	**Sea (35 ‰)**	**Salt**	**Qarun**	**Sea**
Cl	33.33	55.03	NaCI	54.8	79.1
SO4	29.85	7.68	MgSO4	16.1	6.23
HCO3	0.86	0.41	Na_2So4	21.2	-
Na	29.1	30.59	$CaSo_4$	3.11	3.42
Ca	1.22	1.18	$CaCO_3$	0.06	-
Mg	3.12	3.68	Ca $(HCO_3)_2$	0.72	0.54
K	1.14	1.11	KCl	1.71	1.43
Others	1.4	0.32	Mg Cl	-	9.28
			Others	1.82	0.91
Total %	100	100	Total	100	100

Long-term change of water parameters indicated a significant change from 1953 to 2023. As shown in Table (4), the transformation of parameters for each item in Qarun Lake exhibits variety. During the past few decades, the nutrients demonstrated an irregular vibration. For instance, nitrite showed a quick rise from 0.16µg/ l during 1953–1955 **(Naguib, 1958)** to 0.0–98.2µg/ l in 1989 **(Soliman, 1991)**, and then, it declined to 4.46µg/ l in 1995 **(El-Shabrawy & Dumont, 2009)**, before going up again to 12.03µg/ l in 1999-2000 **(Ali, 2002)** to 13.7µg/ l in 2003 **(Sabae & Ali, 2004)**, then reducing to 10.08µg/ l in 2006 **(Abdel-Satar *et al.*, 2010)**, and to 6.1µg/ l in 2011 **(EL-Shabrawy *et al.*, 2015)**, and yet again, rising to 24.9µg/ l in 2012 **(Shadrin *et al.*, 2016)**, and dropped to 12µg/ l in 2013 **(Ibrahim & Ramzy (2013)**, before going up again to 749.87µg/ l in 2016 **(Shaaban *et al.*, 2016)**, then reducing to 60.55µg/ l in 2018 **(Goher *et al.*, 2018)** to 69.48µg/ l in 2020 **(Abd El-Aal *et al.*, 2020)**. Finally, it declined to 36.5µg/ l in 2023 (The present study). The significant variability may be connected to the amount and composition of waste released into the lake through El-Wadi and El- Bats drains. Generally, the contents of nitrite, nitrate, and phosphorus in Qarun Lake exhibited fluctuations but showed a significant increase over time. The values of pH, DO, BOD, COD, TSS, and TDS exhibited limited variation over time.

Table 4. Long-term changes of water quality parameters in Lake Qarun

	Trans Cm	TSS mg/l	TDS g/l	pH	DO mg/l	BOD mg/l	COD mg/l	NH_4 µg/l	NO_2 µg/l	NO_3 µg/l	TN mg/l	PO_4 µg/l	TP µg/l	SiO_4 mg/l
1953-1955[1]	-	-	21.94	8.12					0.16	34.84		0.38		
1989[2]	45				7.6		11.99	89.95	0.0-98.2	307		65.68		17.71
1995[3]	54		38.7	8.4	6.89	4.7	14.9	50	4.46	61.2	7.5	25.6	120	6.7
1999-2000[4]	59.86		34.87	8.2	7.99	6.9	28.2	460	12.03	73.65	73.5	57.99	192.61	6.38
2003[5]	55		32.4	8.4	7.9	5.9	20.9	150	13.7	93.9		59.5	367.7	6.16
2006[6]	61.25		35.31	8.22	9.37	7.24	11.99	378	10.08	38.8		94.02	586.5	3.59
2011[7]	110		33.4	8.3	5.1	4.6	15.1	90.4	6.1	184		31.9	151.6	2.1
2012[8]	84.3		32.6	8.2	8.23	5.7	5.9	26	24.9	160	3.14	45.23	217	10.36
2013[9]	55.5	32.2	34.7	8.1	8.68			35	12	41		92	584	
2014[10]				8.22			11.68	-		19.8		10		
2015[11]				8.32			12.92	-		28.6		80		6.15
2016[12]				7.91	6.43	3.78	32.5	114.3	749.87	325.3		249.93		2.79
2018[13]	57.71	24.32	29.59	8.4	8.32	6.55	24.1	55	60.55	0.3 mg	2.49	26.08	91.97	10
2020[14]	43.96	37.17	33.49	8.31	7.4	6.75	25.33	1120	69.48	0.15	2.05	45.79	132.39	8.74
2022[15]			36	7.5	7.29			-						
2023[16]	22.47	57.55	38.4	8.4	5.01	9.49	31.4	96.5	36.5	0.16	2.01	60.75	112.3	9.99

[1]Naguib, 1958, [2]Soliman, 1991, [3]El-Shabrawy and Dumont, 2009, [4]Ali, 2002, [5]Sabae and Ali, 2004, [6]Abdel-Satar *et al.*, 2010, [7]EL-Shabrawy *et al.*, 2015, [8]Shadrin *et al.*, 2016, [9]Ibrahim and Ramzy 2013, [10]Abu-Ghamja *et al.*, 2018, [11]Abu-Ghamja *et al.*, 2018, [12]Shaaban *et al.*, 2016, [13]Goher *et al.*, 2018, [14]Abd El-Aal *et al.*, 2020, [15]Yosef *et al.*, 2022, and [16]The present study.

TSI

The TSI is a useful tool for evaluating the condition and quality of aquatic environments. According to the quantity of water's biological productivity, it is a categorization method intended to "evaluate" specific lakes. It's important to note that water quality decreases with increasing eutrophy. Lakes are typically divided into three groups: eutrophic, mesotrophic, and oligotrophic. Hypereutrophic lakes are those with extremely high trophic indices. According to **Dodds *et al.* (1998)**, within this measurement framework, each increase of ten units correlates with a halving of Secchi depth, a threefold increase in chlorophyll concentration, and a doubling of total phosphorus. A supplementary Carlson-type index, utilizing total nitrogen concentration, was developed. Utilizing trophic state indices (TSIs), originally proposed by **Carlson (1977)** and later modified by **Kratzer and Brezonik (1981)**, the study sought to evaluate the lake's current trophic status and explore the correlations between four calculated indices: TSI (SD), TSI (Chl-a), TSI (TP), and TSI (TN).

Our data indicated a mid-eutrophic state for most Lake Qarun sites throughout the year, though sites 1, 3, and 6 showed hyper-eutrophic characteristics. The TSI mean value for Qarun Lake varied throughout the year between 62.16 and 85.6, showing a significant fluctuation ($P<0.001$) in both space and time, as shown in Fig. (2). The minimum TSI value was observed at site (5). However, St. (1), which receives effluent from El-Bats drain that is highly loaded with nutrients, has the highest TSI value.

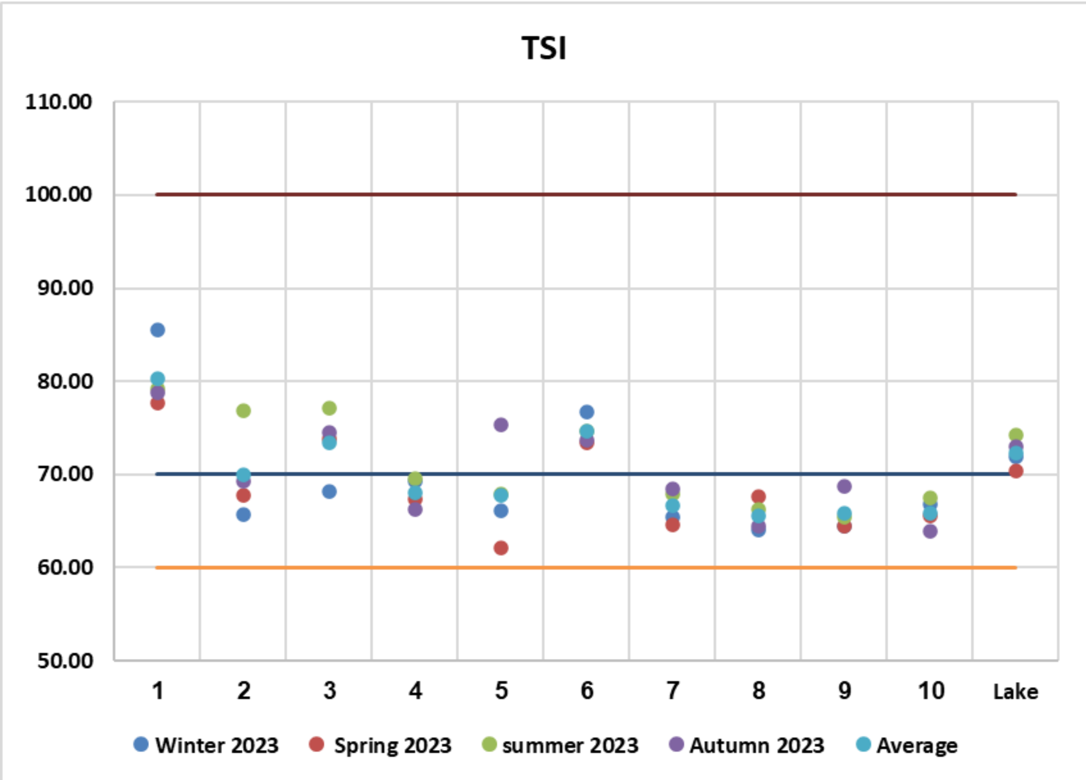

Fig. 2. Seasonal trend of trophic state index for Qarun lake water

OWQI

Water quality indexes are seen as a unique and valuable means of encapsulating the overall water quality in a single phrase, facilitating the selection of the best course of action for dealing with existing problems **(Abu-Ghamja *et al.*,**

2018). Its definition involves evaluating the biological, chemical, and physical quality of water compared to its natural state, human influences, and potential uses.

The OWQI represents water quality through a single value derived from measurements of different water variables. It is preferable to be sensitive to changes in each variable rather than just the one that carries the most weight **(Banda & Kumarasamy, 2020)**. The OWQI for fishing usage is determined by six parameters in our study: temperature, DO, BOD, pH, (ammonia + nitrate), and TP. The findings show that the OWQI is going from 14.0 to 50.0 in Qarun Lake water for fishing usage and is rated as very poor for all locations around the year. Site 1, however, demonstrated the most degraded water quality, reflected in the lowest OWQI score as detailed in Table (5).

Table 6. Categories of OWQI of Qarun lake water

Station	Winter		Spring		summer		Autumn	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank
1	14	Very poor	20	Very poor	16	Very poor	16	Very poor
2	39	Very poor	31	Very poor	14	Very poor	34	Very poor
3	50	Very poor	35	Very poor	14	Very poor	41	Very poor
4	34	Very poor	33	Very poor	14	Very poor	37	Very poor
5	49	Very poor	42	Very poor	14	Very poor	47	Very poor
6	20	Very poor	18	Very poor	15	Very poor	28	Very poor
7	45	Very poor	38	Very poor	20	Very poor	39	Very poor
8	47	Very poor	16	Very poor	19	Very poor	27	Very poor
9	50	Very poor	22	Very poor	19	Very poor	34	Very poor
10	42	Very poor	21	Very poor	15	Very poor	44	Very poor
Lake	38	Very poor	33	Very poor	16	Very poor	35	Very poor

CWQI

To facilitate the interpretation of technical water quality data, the CWQI was developed as an adaptation of the British Columbia Water Quality Index (BCWQI), as cited in **Hagag (2017)**. It condenses data from various water quality parameters into one numerical value, facilitating comparisons of data from different sampling locations **(Elsherif, 2017)**.

In the CWQI computations, several water quality criteria were chosen for aquatic life usage. Temperature, TSS, pH, DO, COD, BOD, NH_4-N, NO_3-N, NO_2-N, and HMs were among the variables. The current findings show that at the various sites, the CWQI was in the range of 41–58 and is classified as marginal at all sites, except sites 1 and 6 which are rated as poor (Table 6).

Table 6. Canadian Water Quality Index of Qarun Lake water for aquatic life

Label	CWQI	Category
1	41	Poor
2	52	Marginal
3	48	
4	57	
5	49	
6	42	Poor
7	54	Marginal
8	58	
9	58	
10	58	
Average	47	

ATI

When assessing the fish life in Qarun Lake water, the ATI takes into consideration a few heavy metal parameters. Its development aimed at evaluating the condition of aquatic ecosystems and ascertaining whether water quality met the requirements for diverse fish species. Due to the existence of a comprehensive toxicity database for fish, toxic effects resulting from different water quality conditions have been used as health indicators for aquatic ecosystems **(Gupta & Gupta, 2021)**. ATI is commonly applied to water quality parameters. In the present study, the water quality variables used were pH, DO, NH_4^+, K^+, PO_4^{3-}, Mn, Zn, Cu, Ni, and Pb.

The findings showed that the Lake water is suitable for all fish life in all location, except station 1 that is suitable only for hard fish (Table 7). ATI values around the year ranged from 58.15 to 78.82. The minimum ATI value was found in winter at St 8, but the maximum value was found during the autumn at St 4.

There is a discrepancy between the water quality assessment by TSI, OWQI, and CWQI, which show poor quality, and the ATI, which suggests the parameters used in its calculation are not the primary causes of Lake Qarun's degradation.

Table 7. ATI categorization of Qarun Lake water

Station	winter	spring	summer	Autumn	Average	Rank
1	60.72	64.21	56.25	56.69	58.15	Suitable only for hardy fish species
2	74.88	72.75	59.97	74.15	70.06	Suitable for all fish life
3	76.68	70.98	63.46	81.44	73.50	Suitable for all fish life
4	83.01	66.85	66.64	74.34	72.66	Suitable for all fish life
5	85.92	84.76	65.24	72.07	75.86	Suitable for all fish life
6	65.07	66.99	67.85	67.10	67.50	Suitable for all fish life
7	81.08	79.96	64.54	71.33	74.59	Suitable for all fish life
8	79.37	76.76	64.73	70.95	73.29	Suitable for all fish life
9	78.48	82.89	64.44	75.33	77.45	Suitable for all fish life
10	77.07	82.98	67.17	73.99	78.82	Suitable for all fish life
Lake	76.61	77.23	64.99	72.24	76.61	Suitable for all fish life

Heavy metals in water

The data obtained demonstrated that heavy metal levels were distributed within the ranges of 174.33 – 412.83µg/ l, 28.54 – 82.71µg/ l, 26.07 – 59.62µg/ l, 2.73 – 18.69µg/ l, 1.06 – 6.24µg/ l, 2.06 – 13.65µg/ l, 6.11 – 30.61µg/ l, 5.14 – 51.96µg/ l, 0.511–1.159µg/ l and 79.25 – 216.48µg/ l, for Fe, Mn, Zn, Cu, Co, Ni, Cr, Pb, Cd and Al in the water of Qarun Lake, respectively (Table 8). Fe, Mn, Zn, Ni, Cr, Co, Al, Pb and Cd showed a high spatially and temporally notable variation ($P<$ 0.01). Copper showed spatially notable variation ($P<0.05$) and a high temporally notable variation ($P<$ 0.001).

Seasonal shifts in heavy metal concentrations within the lake's water samples are likely due to the variable input of sewage effluents, industrial wastes, and agricultural runoff **(Mousa *et al.*, 2017)**. The increased presence of heavy metals in Lake Qarun water during warmer periods can be attributed to the liberation of metals from sediments into the overlying water, a process facilitated by fermentation and organic matter breakdown under higher temperatures **(Goher *et al.*, 2014)**. Additionally, the increase in water evaporation rate brought on by the higher water temperature results in an increase in metal levels **(Tafa & Assefa, 2014)**. This finding is consistent with reports from **Authman *et al.* (2015)** and **Helmy *et al.* (2020)**, which recommended the usage of pesticides, fertilizers containing cadmium and lead, agricultural chemicals, and using sewage sludge as fertilizer on farmland might lead to water pollution. Table (9) shows the HM levels in El-Bats and El-Wadi drains.

Table 8. Heavy metals concentrations (µg/l) in Qarun Lake water

Parameter	Winter	Spring	Summer	Autumn	Range	Mean ± SD
Fe (µg/l)	**222-376**	**174-338**	**236-412**	**249-388**	**174-412**	**289.32±55.65$^{a, b}$**
Mn (µg/l)	**28.54-62.12**	**37.59-58.22**	**52.35-82.7**	**38.79-66.27**	**28.54-82.7**	**50.01±14.4$^{a, b}$**
Zn (µg/l)	**29.7-53.8**	**26.07-44.1**	**35.3-55.08**	**37.4-59.6**	**26.07-59.6**	**38.31±7.9$^{b, d}$**
Cu (µg/l)	**5.16-10.55**	**2.73-11.4**	**7.45-18.69**	**8.79-16.86**	**2.73-18.69**	**9.44±3.77$^{b, f}$**
Co (µg/l)	**1.06-4.16**	**1.33-4.32**	**1.76-6.24**	**1.68-5.96**	**1.06-6.24**	**2.63±1.24$^{a, b}$**
Ni (µg/l)	**5.94-10.16**	**2.06-6.06**	**6.35-13.65**	**7.68-13.41**	**2.06-13.65**	**7.68±2.82$^{a, b}$**
Cr (µg/l)	**11.55-22.42**	**6.11-14.25**	**12.91-25.16**	**12.41-30.61**	**6.11-30.61**	**15.02±5.01$^{a, b}$**
Pb (µg/l)	**14.15-32.8**	**5.14-23.56**	**20.22-51.96**	**15.14-34.16**	**5.14-51.16**	**21.94±9.18$^{b, d}$**
Cd (µg/l)	**0.511-0.91**	**0.63-0.95**	**0.71-1.16**	**0.67-0.99**	**0.51-1.16**	**0.80±0.12$^{c, d}$**
Al (µg/l)	**86.7-201.7**	**79.3-188.6**	**106.9-216.5**	**119.7-204.2**	**79.3-216.5**	**133.3±37.5$^{a, b}$**

Letter symbols represent significant difference: a: $P < 0.001$ spatial variations, b: $P<0.001$ temporal variations, c: $P< 0.01$ temporal variations, d: $P< 0.01$ spatial variations and f: $P< 0.05$ spatial variations.

Table 9. Heavy metals concentrations (µg/l) in El Bats and El Wadi drains water

Parameter	Winter	Spring	Summer	Autumn	Range	Mean ± SD
Fe (µg/l)	**429-473**	**399-362**	**466-444**	**249-388**	**249-473**	**363±38.3$^{a, b}$**
Mn (µg/l)	**53.6-56.4**	**62.4-68.1**	**64.2-81.2**	**52.1-56.1**	**52.1-81.2**	**57.7±9.6$^{a, b}$**
Zn (µg/l)	**53.2-59.4**	**52.87-65.13**	**56.08-64.73**	**54.2-62.3**	**52.87-65.13**	**44.07±17.0$^{b, d}$**
Cu (µg/l)	**15.37-18.4**	**12.87-14.05**	**15.69-16.08**	**15.19-26.9**	**12.87-26.94**	**14.01±5.2$^{b, f}$**
Co (µg/l)	**3.76-4.64**	**4.12-4.87**	**5.99-8.16**	**3.98-4.16**	**3.76-8.16**	**3.77±1.5$^{a, b}$**
Ni (µg/l)	**15.99-16.72**	**5.73-9.49**	**11.48-13.58**	**13.73-15.06**	**5.73-16.72**	**10.7±3.4$^{a, b}$**
Cr (µg/l)	**18.66-25.8**	**15.6-22.8**	**26.55-29.4**	**34.27-35.22**	**15.62-35.22**	**21.68±6.9$^{a, b}$**
Pb (µg/l)	**29.7-37.3**	**21.12-31.3**	**36.9-43.7**	**32.08-35.2**	**21.12-43.7**	**29.39±6.6$^{b, d}$**
Cd (µg/l)	**1.11-1.18**	**1.38-1.43**	**1.51-2.61**	**1.29-1.39**	**1.11-2.61**	**1.23±0.47$^{c, d}$**
Al (µg/l)	**217.6-231.9**	**196.1-209.4**	**221.1-251.7**	**209-226.4**	**196.1-251.7**	**181.6±16.9$^{a, b}$**

Letter symbols represent significant difference: a: $P < 0.001$ spatial variations, b: $P<0.001$ temporal variations, c: $P< 0.01$ temporal variations, d: $P< 0.01$ spatial variations and f: $P< 0.05$ spatial variations.

Stations 1 and 6, facing the entrance of the El Bats and El Wadi drains, had the highest heavy metal concentrations. A robust positive relationship was observed among various heavy metals (n= 40, $p< 0.01$) Fe/Mn (r = 0.64), Fe/Zn (r = 0.64), Fe/Cu (r = 0.53), Fe/Cr (r = 0.64), Fe/Ni (r=0.62), Fe/Co (r = 0.67), Fe/Al (r=0.76), Fe/Cd (r=0.55), Fe/Pb (r=0.63), Cr/Ni (r=0.80), Cr/Co (r=0.69), Cr/Al (r=0.68), Cr/Pb (r=0.61), Cr/Cd (r=0.48), Ni/Co (r=0.73), Ni/Al (r=0.58), Ni/Pb (r=0.67), Ni/Cd (r=0.63), Ni/Mn (r= 45) which confirmed the same origin and source. Conversely, a negative correlation of DO and pH with the metal, such as Fe/DO (r=-0.57), Zn/DO (r=-0.66), and Zn/pH (r=-0.60) shows how high dissolved oxygen and pH contribute to the precipitation of different metals in bottom sediment **(Goher, 2019; Abd El-Aal *et al.*, 2020)**.

Metal pollution ondices

Pollution index (PI)

Based on the PI value for the aquatic life criteria, Fe, Zn, Ni, Cr, and Cd showed no pollution in various locations, while Co and Mn, and Pb exhibited slightly polluted effects in the eastern sector. On the other hand, Cu shows a strong pollution effect at 1 and varied pollution degrees from slightly to moderately affecting the aquatic organisms at the other sites (Table 10).

Table 10. MI values of the studied HMs in Qarun Lake water for aquatic organisms

Station	Cu		Pb		Zn		Fe		Ni	
	PI	Effect	PI	Effect	PI	Effect	PI	Effect	PI	Effect
1	3.04	strongly	2.56	moderately	0.41	No	0.26	No	0.90	No
2	1.88	slightly	1.74	slightly	0.29	No	0.19	No	0.82	No
3	2.54	moderately	1.54	slightly	0.31	No	0.19	No	0.62	No
4	2.30	moderately	1.30	slightly	0.34	No	0.19	No	0.56	No
5	2.01	moderately	1.66	slightly	0.31	No	0.17	No	0.51	No
6	2.92	moderately	2.14	moderately	0.42	No	0.23	No	0.73	No
7	2.27	moderately	1.34	slightly	0.35	No	0.20	No	0.67	No
8	2.26	moderately	1.58	slightly	0.33	No	0.18	No	0.57	No
9	1.74	slightly	1.21	slightly	0.31	No	0.17	No	0.58	No
10	1.73	slightly	1.18	slightly	0.30	No	0.18	No	0.55	No
Lake	2.24	moderately	1.60	slightly	0.34	No	0.20	No	0.65	No
Station	Co		Cd		Mn		Cr			
	PI	Effect	PI	Effect	PI	Effect	PI	Effect		
1	3.68	strongly	0.09	No	3.68	strongly	0.09	No		
1	3.68	strongly	0.09	No	3.68	strongly	0.09	No		
1	3.68	strongly	0.09	No	3.68	strongly	0.09	No		
2	2.13	moderately	0.09	No	2.13	moderately	0.09	No		
3	1.87	moderately	0.08	No	1.87	moderately	0.08	No		
4	1.38	slightly	0.07	No	1.38	slightly	0.07	No		
5	1.50	slightly	0.07	No	1.50	slightly	0.07	No		
6	2.18	moderately	0.08	No	2.18	moderately	0.08	No		
7	2.08	moderately	0.08	No	2.08	moderately	0.08	No		
8	1.51	slightly	0.07	No	1.51	slightly	0.07	No		
9	1.15	slightly	0.07	No	1.15	slightly	0.07	No		
10	1.19	slightly	0.07	No	1.19	slightly	0.07	No		
Lake	1.86	slightly	0.08	No	1.86	slightly	0.08	No		

Heavy metals pollution index HPI

According to **Balakrishnan and Ramu (2016)**, the HPI is a measure of the overall quality of water and helps determine and quantify trends in water quality related to heavy metals. Based on an arithmetic quality mean ranking system, this index was created **(Giri & Singh, 2014)**. The results indicated that all of the chosen locations around the lake are gravely endangered by metal pollution, based on the metal pollution index values (HPI > 100). According to Table (11), site (1) is the most polluted site, with an HPI ranging from 152.68 to 405.85.

Table 11. Heavy metal pollution index of the assessed heavy metals in Qarun Lake water based on guideline levels for aquatic organisms

Station	HPI value	Category
1	405.85	Polluted
2	244.96	
3	238.09	
4	185.31	
5	183.43	
6	275.04	
7	232.64	
8	187.91	
9	152.68	
10	159.31	
Lake	226.80	

HMs in fish

This study utilized *Oreochromis niloticus* from Lake Qarun to analyze metal accumulation patterns **(Abdel-Khalek *et al.*, 2015)**. Tilapia are well-suited as bioindicators for heavy metal effects, frequently used in toxicological research **(Osman *et al.*, 2010)**, and possess traits that make them effective for assessing aquatic system quality and metal pollution **(Ghannam, 2021)**. The tendency of trace metals to accumulate in various organs poses a threat to fish, with subsequent implications for human and animal health.

Analysis of fish tissues from Lake Qarun showed that the highest metal concentrations were found in fish collected from the eastern sector. Specifically, iron, manganese, zinc, copper, cobalt, nickel, chromium, aluminum, lead, and cadmium were detected, with iron and aluminum exhibiting the most significant accumulation. These findings suggest that the eastern part of the lake experiences the highest pollution levels (Fig. 3). Fish can absorb trace metals and dissolved elements from the water. These metals build up in large quantities in different tissues and have toxicological effects that meet specific criteria. Fig. (3) illustrates how the heavy metals are distributed across various tissues of *Oreochromis niloticus* that were gathered from the western and eastern sectors of Qarun Lake. Results obtained showed that liver and kidney were accumulated with high level of metals compared to other tissue; in contrast, the fish body muscle had the lowest metal content. Overall, the average metal concentrations in *Oreochromis niloticus* followed a consistent pattern: liver > kidney > gills > gonad > muscle. ANOVA revealed a highly notable variation ($P < 0.001$) in HMs levels within liver tissues between fish from the eastern and western sectors of the lake. Table (12) compares the average HMs levels in the muscle tissue of tilapia (*O. niloticus*) sourced from Qarun Lake with international standard values.

Generally, Table (12) shows that the highest values of Pb were greater than the equivalent standard limits of and 0.5 **(FAO, 1983)**, 0.5 **(FAO/WHO, 1989)**, 0.1 **(EU, 2001)**, and 0.2 **(EC, 2005)**, the maximum levels of Cu, Mn, and Fe, were clearly lower than the standard levels. However, it was shown that the levels of Ni buildup were above the recommended range of 0.5–0.6µg/ g according to **FAO (1983)**. In a similar vein, Cr went above the **ANZECC (2000)** maximum guideline of 0.15. The recommended level of manganese was more than 1µg/ g **(FAO, 1983)**. Lastly, Cd exceeded the relevant standard values of 0.5 **(FAO/WHO 1989)**, 0.2 **(MAFF, 2000)**, 0.2 **(ANZECC, 2000)**, and 0.05 **(EC, 2005)**.

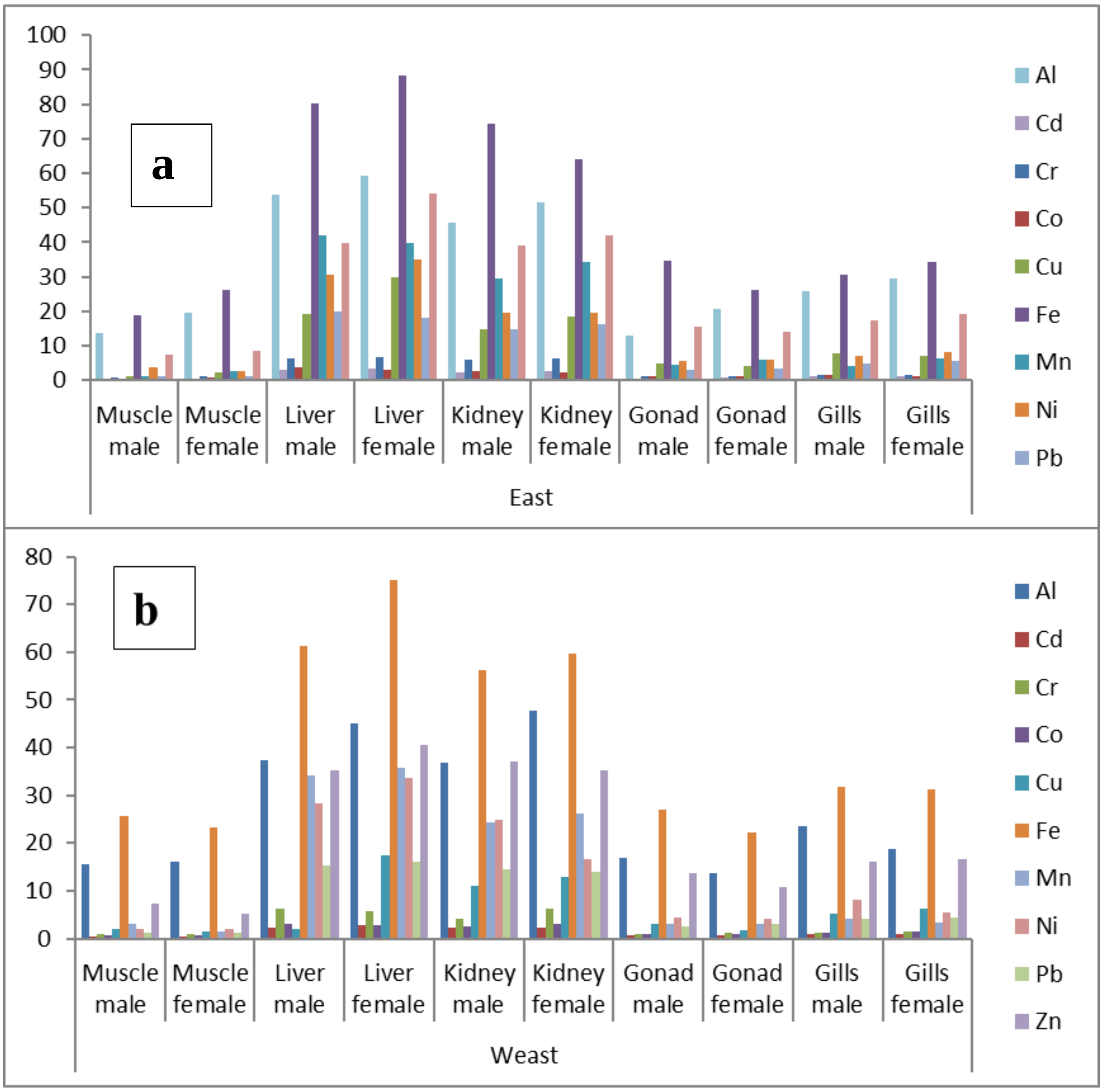

Fig. 3. The HMs levels in the different organs of Tilabia in the **(a)** east and (b) west sectors of Qarun Lake

Table 12. Concentration ranges of metals (µg/kg ww) of the Nile tilapia muscles in Qarun Lake compared to standard levels

Organization	Reference	Fe	Mn	Zn	Cu	Co	Ni	Cr	Pb	Cd	Al
European Community	**EC (2005)**								0.2	0.05	
England	**MAFF (2000)**			50	20				2	0.2	
FAO	**FAO (1983)**			30	30		0.5-0.6	0.15-1.0	0.5		
Turkish guidelines	**Dural *et al.*, (2007)**		20								
FAO/WHO limits	**FAO/WHO (1989)**			40	30				0.5	0.5	
EU limits	**EU (2001)**				10				0.1	0.1	
WHO	**WHO 1989**	100	1	100	30						
ANZECC*	**ANZECC (2000)(a)**								2	0.2	
USFAD	**USFAD (1993a)(b)**										
USFAD	**USFAD (1993b)(b)**										
Present study	**East**	22.38	1.86	7.82	1.82	0.68	3.31	0.98	1.13	0.47	16.70
Present study	**Weast**	24.41	2.25	6.35	1.81	0.62	1.98	0.95	1.12	0.36	40.96

*µg/kg dry-weight (a) according to **El-Sayed *et al.* (2011)** after **ANZECC (2000)**; (b) according to **Taoheed and Said (2014)** and **Javed and Usmani (2014)** after **USFAD (1993)**.

Bio-accumulation factor (BAF)

Each metal's bioavailability in the water is among the factors that correlate with the bio-concentration and bioaccumulation of HMs in fish tissues. This is influenced by temperature and pH levels **(Pinheiro *et al.*, 2019)**. The buildup of metals in fish is a complex process influenced by a multitude of variables: the fish's species, the length of exposure, its trophic status, nutritional intake, life stage, body size, metabolic rate, and the efficiency of its detoxification and absorption systems **(Gashkina, 2024)**. In our investigation, cadmium stood out as the metal with the most pronounced accumulation, exhibiting BAF values that fluctuated significantly, from 377.1 to 3923µg/ g, within both muscle and liver tissues. The lowest values were found for Fe, which varied from 65.6µg/ g in muscle to 309.8µg/ g in liver. Generally, the liver and kidney exhibited the highest BAFs for all metals in all organs, whereas the muscles had the lowest concentrations. This is because of their physiological functions in fish metabolism **(Tapia *et al.*, 2012; El-Agri *et al.*, 2021)**. A proportional relationship exists whereby the quantity of pollutants accumulated in fish livers mirrors the level of environmental contamination in their surrounding waters. It has been demonstrated that the target tissues for heavy metals are those that are metabolically active. As an example, the liver and kidneys are vital organs that significantly contribute to excretion and homeostasis **(Shahida *et al.*, 2021)**. Because of this, metal accumulation occurs in these tissues at a higher rate than in other tissues, such as muscles, where metabolic activity is relatively modest **(Goher *et al.*, 2017)**.

The increased metal accumulation ratios in the liver may therefore be attributed to the activity of cystine residues of metallothionein, proteins that demonstrate a high affinity for select metal ions, like Zn, Cd, and Cu, decreasing their harmfulness and letting the liver to build up high concentrations **(Uysal *et al.*, 2009)**. The liver, vital for xenobiotic detoxification and removal, is susceptible to morphological modifications under certain toxicological stressors **(Rocha & Monteiro, 1999)**. **Avenant-Oldewage (2014)** asserts that the kidney may have a secondary role in detoxification, with the liver serving as the primary organ. According to the current investigation, liver tissues had the highest levels of Fe, Cu, and Cd bioaccumulation (Fig. 4). This study's results corroborate the findings of **Elwasify *et al.* (2021)**, who observed elevated bioaccumulation factors for cadmium and iron in fish organs. According to **El-Agri *et al.* (2021)**, cadmium may have accumulated highly in fish liver because of its strong interaction with metallothionein cysteine residues. Since the kidney was shown to contain greater levels of several HMs in examined fish, where the accumulation of heavy metals in the kidney is enhanced by the presence of metallothionein, a protein capable of binding metals **(Ishaq *et al.*, 2011)**. On the other hand, the observed low metal concentrations in fish muscle suggest a potential correlation with reduced levels of metallothionein (MTs) binding proteins within the tissue **(Rauf *et al.*, 2009)**. Since muscles are used for both human and animal food, their metal content is frequently checked **(Alibabic *et al.*, 2007)**.

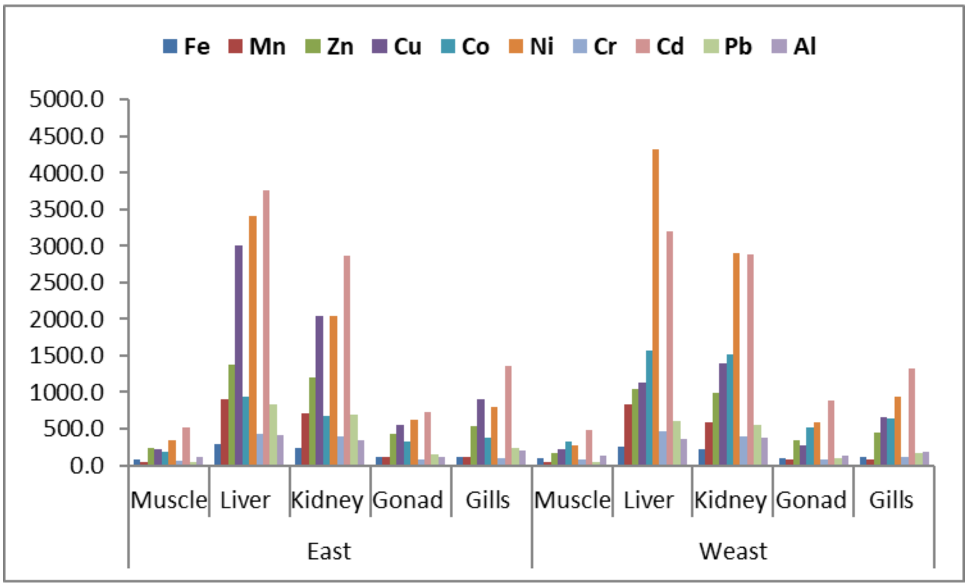

Fig. 4. Bioaccumulation factor of metals in various organs of *O. niloticus* from Qarun Lake

Human health risk

By identifying, characterizing, and analyzing toxic substances, risk assessment determines the likelihood of negative health outcomes in humans within a given timeframe **(Sánchez *et al.*, 2022)**. This approach was employed to evaluate the exposure and risk associated with consuming contaminated fish from Lake Qarun, using human health as the primary reference point using the ten detected metals to compute (THQ) and (HI) values. Consumption of fish with a THQ or HI below one does not pose a health concern, but the greater the extent to which THQ and HI exceeds one, the greater the risk involved **(USEPA, 2013)**. According to **Ukoha (2014)**, HI < 1 means no hazard; 1 < HI < 10 means moderate hazard, while > 10 means high hazard or risk.

The present results indicated that the THQ values obtained from the exposure route for all investigated metals do not indicate a risk associated with consuming *O. niloticus* from Qarun Lake (THQ < 1). The non-carcinogenic hazards to humans from heavy metals, specifically via ingestion of fish tissues, by computing THQ and HI indices for the ten metals analyzed is presented in Fig. 5. The THQ calculated for the ingestion of analyzed metals through *O. niloticus* in the eastern sector demonstrated a risk hierarchy order of Co (THQ= 0.722) > Cr (THQ= 0.207) > Cd (THQ = 0.148) > Pb (THQ = 0.103) > Ni (THQ = 0.053) > Cu (THQ= 0.014) > Fe (THQ= 0.010) > Zn (THQ = 0.008) > Al (THQ = 0.005) > Mn (THQ = 0.004), while in the west sector were Co (THQ = 0.655) > Cr (THQ = 0.202) > Cd (THQ = 0.115) > Pb (THQ = 0.102) > Ni (THQ = 0.031) > Cu (THQ = 0.014) > Fe (THQ = 0.011) > Zn (THQ = 0.007) > Al (THQ = 0.005) = Mn (THQ = 0.005). Consequently, based on *O. niloticus* consumption. As a result, no non-carcinogenic health risks are associated with the individual ingestion of these metals through the consumption of *O. niloticus* from Qarun Lake according to **Custodio *et al.* (2021)**.

To appropriately evaluate the health risks associated with consuming tilapia fish from Lake Qarun, it is crucial to account for the combined impact of the studied heavy metals. Consequently, the Hazard Index (HI) is indispensable for this assessment **(Yacoub *et al.*, 2021)**. The findings demonstrated that fish in the east and west sites have total non-carcinogenic hazard indices (HI) of 1.275 and 1.148, respectively. This finding showed that there was a low probability of risk because of the ingesting of the muscle tissue of *O. niloticus* harvested from Qarun Lake, according to **Ukoha (2014)**.

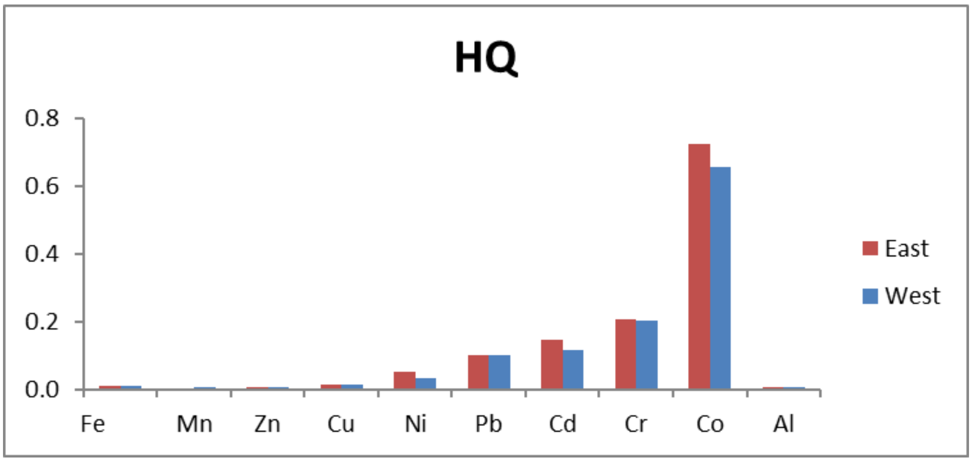

Fig. 5. THQ to human population for heavy metals through *O. niloticus* from Qarun Lake

CONCLUSION

Lake Qarun, an ancient Egyptian water basin located within the Fayoum province, is a closed saline lake receiving substantial waste input primarily via the El-Bats and El-Wadi drains. This study, utilizing various WQIs, demonstrates a clear deterioration in water quality across all sectors of Lake Qarun, particularly near drainage sources. Notably, the eastern segment of the lake exhibits a marked concentration of measured heavy metals, directly attributable to diverse effluents from the El-Bats Drain. Pollution Indices indicate overall heavy metal pollution in Lake Qarun, potentially posing adverse effects on aquatic organisms. Generally, the bioaccumulation order of heavy metals in *Oreochromis niloticus* muscle tissue was Cd > Ni > Cu > Co > Zn > Mn > Pb > Al > Cr > Fe. While the THQ for individual heavy metals in *Oreochromis niloticus* remained below the hazard limit (THQ < 1), the HI for combined metals exceeded the threshold value (HI > 1), suggesting potential adverse effects for consumers of tilapia from Lake Qarun, with a relatively higher risk associated with the eastern sector. This study underscores the critical importance of concerted efforts to address the pollution issues plaguing Lake Qarun and to restore it to its former ecological health.

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