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Evaluation of heavy metals contents and the possible risk in the surface water and fish of Lake Qarun, Egypt

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ABSTRACT

Lake Qarun is Egypt's third-biggest lake, with an enclosed water system. The only source of water intake in the lake is drainage water, while evaporation is the only outflow path. This source of pollution affects water and fish; therefore, it threatens food security, which is an essential multi-dimensional goal in the United Nations 2030 Agenda. Fish contaminated with heavy metals are unsafe for humans and may cause serious health problems. Hence, this study aimed to determine the seasonality of heavy metals contents in the surface water and tissues of fishes (*Tilapia zillii* and *Mugil cephalus*) to assess and match the different exposure routes and possible health risks related to heavy metals in Lake Qarun. Various indices were estimated in the present research, based on the levels of heavy metals in the surface water and fish of the lake including heavy metal evaluation index (HMEI), chronic daily intake (CDI), target hazard quotient (THQ), hazard index (HI), carcinogenic health hazard (CHH), metal pollution index (MPI), estimated daily intake of heavy metals (EDI), and target cancer risk (TR). Additionally, the inverse distance weighting (IDW) technique from GIS was used to map the spatial distribution of the heavy metals in the lake during the seasons of summer and winter. Results revealed that higher metal contents were recorded in surface water and fish tissue samples during summer compared to winter. Moreover, the highest metal concentrations were reported in the eastern section of the lake. No health hazards were detected, either persuaded by the ingestion or dermal contact of Lake Qarun surface waters, while serious health hazards were recorded from the ingestion of both fish (especially *T. zillii*) during the study. Therefore, the residents and fishermen in the study area should be forewarned since they are highly exposed to all routes of health hazards related to heavy metals contents in the lake. In addition, an immediate consideration is necessary to avoid the continuous abuse of the lake by untreated sewage and agricultural effluents that limit the potential of Lake Qarun.

INTRODUCTION

Lakes are vulnerable to natural and man-made changes, thus they can be used as indicators of various effects of climate change and anthropogenic activity. Lake Qarun is one of Egypt's oldest lakes and the third lake in terms of area. It is a shallow (2-5 meters) closed water system located in a fertile area, which supports a massive rural population at the rim of the great western Egyptian desert called El-Fayoum Depression in El-Fayoum Governorate. Lake Qarun serves as a tank extending over 6068 km^2 **(Abdel Wahed, 2015)**. Moreover, it is one of Egypt's most significant fisheries sectors, with a high number of commercially important species and a substantial overall catch **(Shehata *et al*., 2017)**. It features a distinct environment that has piqued the interest of various authors, and it has a historical and scientific significance. The lake receives agricultural and municipal wastewaters that are mostly discharged from El-Batts and El-Wadi drains, together with other ten inferior drains poured into the lake through several hydraulic pumps **(Shadrin *et al*., 2016)**. Geographically, Lake Qarun is situated in the Egyptian barren domain, which is characterized by a hot dry climate most of the year, with high evaporation rates and limited rainfall **(Baioumy *et al*., 2010)**.

For the lake hydrology, it is extremely affected by the growing pollution since it annually receives massive agricultural drainage and sewage wastewaters **(Goher *et al*., 2018)**. Annually, the lake receives about $338*10^6$ m^3 of drainage water from both drains of El-Bats and El-Wadi, as well as more than 67.8 $*10^6$ m^3 of effluents from other sources. However, the lake loses approximately 415 $*10^6$ m^3 every year via evaporation, which is the only flow-out path from the lake **(Abdelbaki, 2021)**.

Although the surface water from the principal supplier is municipal water, it suffers from different sources of contamination owing to their massive size and availability of effluents. Many pollutants in the watershed are poisonous with a potential human health risk such as heavy metals (HMs). Heavy metals are inorganic pollutants with confirmed potential ecological, biological, and health hazards **(Makokha *et al*., 2016)**. Contamination of surface water bodies with heavy metals has gained a global attention concerning eco-toxicity **(Reddy *et al*., 2004)**, aggregation pathway **(Yuan *et al*., 2004)**, ecological risks **(Huang *et al*., 2016)**, as well as the possible human health hazards **(Salaah & El-Gaar, 2020)**.

Prolonged direct dermal contact, inhalation, and the ingestion of heavy metals have been linked to several serious health problems in humans, viz. anemia, acute leukemia and eye cataracts in addition to various carcinogenic risks **(Yang & Massey, 2019; Khaled *et al*., 2020)**. Hence, scientists have studied the potential human health risks associated with heavy metals in polluted waters **(Salaah & El-Gaar, 2020; Ahmed *et al*., 2022)**.

Although science is capable of precisely predicting the possible mechanisms of preventing or alleviating the undesirable consequences of the anthropogenic activities, researchers have developed many prediction tools, which can effectively deliver an early warning of ecosystem deterioration, associated with the inputs of pollutants **(Hussein *et al*., 2008)**.

The GIS is a significant tool in tackling environmental problems in a variety of fields, such as engineering and environment. Applying the geostatistical analysis approach in GIS applications enables the interpolation technique to anticipate the value of attributes at un-sampled sites from measurements taken at locations within the same region. It can be described as a set of approaches or tools used for predicting the values of variables distributed in space or time. It helps investigate the sample data and create interpolated maps. Inverse distance weighting (IDW) is a commonly and easily used automatic tool that has been carefully designed to operate well for this application. This technique has been widely used in various research studies to assess water quality in Qarun Lake and other regions worldwide **(El-Zeiny & Elbeih, 2019; Al-Shaibah *et al*., 2021; Oseke *et al*., 2021)**.

Aligned with this trend, the present work was conducted to:

(1) Evaluate the distribution of heavy metals in Lake Qarun surface water and two fish species (*T. zillii* and *M. cephalus*);

(2) Compare the heavy metals load in various organs of the two fish species;

(3) Investigate and match the different exposure routes and the possible health hazards consequences, associated with heavy metals contents through dermal, ingestion of surface water, and fishes from Lake Qarun;

(4) Detect the spatial allocation of heavy metals in the lake using GIS technique.

MATERIALS AND METHODS

Study area and sampling

Lake Qarun is Egypt's third-biggest lake with an area of about 240 Km^2, and one of the largest enclosed saline water systems in North Africa (Fig. 1). Due to the continuous flow of pollutants into the lake, it became the most threatened lake in Egypt **(Mohamed *et al*., 2022**). In 1989, the Lake was identified as a protected area and has been assigned as a significant bird area in 2001, as well as a wetland in 2012 by the Ramsar Convention. It lies in the North of El-Fayoum depression at longitudes of 30° 240 0800 & 30°4905700 E, and latitudes of 29° 240 2600 & 29° 320 04.7400 N.

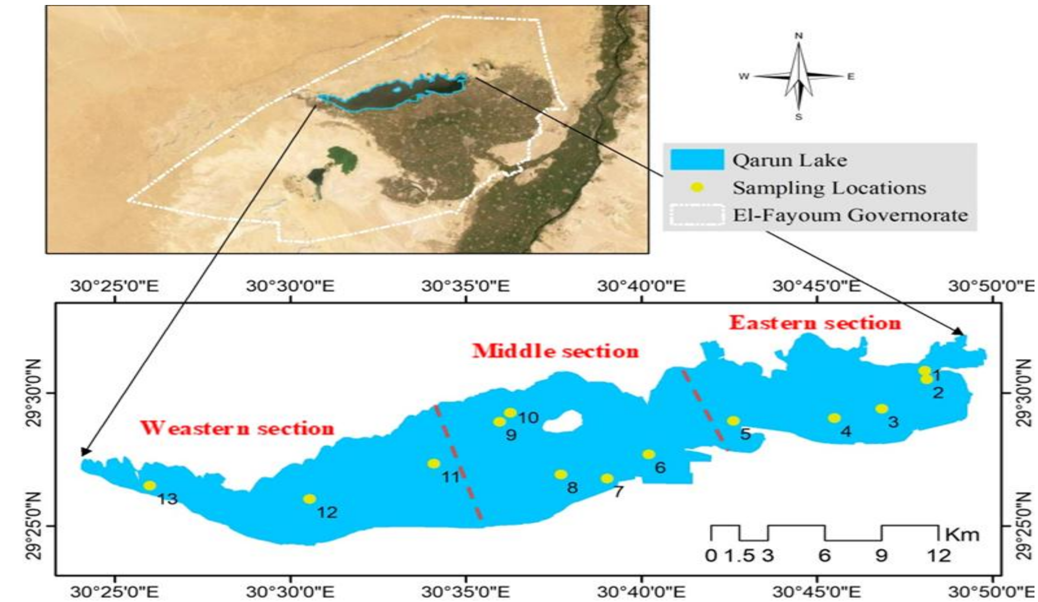

Fig. 1. (A) A satellite map showing the location of lake Qarun in relation to El-Fayoum Governorate, Egypt, (B) Sections of Lake Qarun, and the yellow dots represent the sampling locations.

Surface water and fish samples were randomly collected from Lake Qarun during the winter and summer seasons of 2021. Water samples (≤15 cm depth) were collected from thirteen sites covering the lake (Fig. 1) and were kept in polypropylene bottles for analyses. The estimation of heavy metals (Fe, Mn, Zn, Cu, Pb, Cd, and Ni) in water was conducted according to the method of **APHA (2005)**, using the atomic absorption reader (GBC model: Savant Graphite Furnace 5000).

Water analysis

GIS analysis

In the current research, the geographic location of all the sampling locations was converted into a GIS layer attributed with the measured heavy metals during the two field visits using ArcGIS. The IDW interpolation approach in GIS was used to analyze the spatial variation in the heavy metals in Qarun lake water including (Fe, Cu, Pb, Zn, Cd, Mn and Ni). This technique helps in producing spatial variability maps in order to determine the contributory variables to pollution accumulation and nutrients loading in the lake. The IDW has long used a deterministic model approach in which undetermined values are computed, based on the proximity of the points rather than the distant values. This interpolation method has been widely utilized in the field of spatial analysis to explain the distribution of pollutants and physicochemical determining patterns in time and space **(Kanagaraj & Elango, 2016; Oseke *et al*., 2021)**.

Heavy metal evaluation index (HMEI)

HMEI expresses a numeric value of water quality based on the heavy metals' concentrations. According to **Singh *et al*. (2017)**, water is considered "Fit" for human usage when HMEI ≤1.0 and "Unfit" when HMEI values >1.0. HMEI was evaluated using the following equation:

$$HMEI = \sum_{i=1}^{n} HM_{(conc.)} / HM_{(MPC)}$$

Where, HM (conc.) represents the concentration of specific heavy metal (mg/L); HM $_{(MPC)}$ is the permissible standard of the same heavy metal for drinking **(USEPA, 2018)** and irrigation **(FAO, 2019)** purposes.

Health hazard assessment of surface water

The human non-carcinogenic risks of heavy metals in surface water were estimated through the ingestion and dermal exposure in the study area. Both hazard quotients (HQ) and hazard index (HI) were applied to analyze the potential hazards for adults.

The chronic daily intake (CDI)

CDI was calculated according to **USEPA (2004)** of both the ingestion and dermal contacts of heavy metal existed in water as follows:

$$CDI_{(ingestion)} = \frac{Cm \times DI \times ABS \times EF \times ED}{BW \times AT}$$

$$CDI_{(dermal)} = \frac{Cm \times SA \times K_p \times ABS \times ET \times EF \times ED \times CF}{BW \times AT}$$

Where, DI is the daily average intake (L/day); ABS is the absorption factor; EF is the exposure frequency (days/year); ED refers to exposure duration (year); CF is the unit conversion; BW is the body weight (Kg); AT is the average time (day); SA is the skin surface area (cm^2); K*p* is the permeability coefficient (cm/hour); ET refers to the exposure time (hour/event), and CF is the conversion factor (L/cm^3).

Target hazard quotient (THQ)

The THQ is used to calculate the relation between the probable exposures to heavy metals, and determine the safe level which doesn't induce adverse health effects in humans using **USEPA (2004)** equations:

$$THQ_{(ingestion)} = \frac{CDI_{(ingestion)}}{RfD_{(ingestion)}} \qquad THQ_{(dermal)} = \frac{CDI_{(dermal)}}{RfD_{(dermal)}}$$

Where, RfD is the reference dose of each metal (mg/Kg Day) for ingestion and dermal absorption of water according to **USEPA (2011)** guidelines. The HQ expresses potential health hazards when HQ ≤ 1.0.

Hazard index (HI)

The HI is the aggregation of total heavy metals THQ; it represents the possible health non-carcinogenic hazards induced by heavy metals in water using the USEPA equations. HI ≤ 1.0 indicates no hazardous human health effects are expected.

$$HI_{(ingestion)} = \sum_{i=1}^{n} (HQ_{ingestion}) HQ_{Fe} + HQ_{Mn} + HQ_{Zn} + \cdots \qquad HI_{(dermal)} = \sum_{i=1}^{n} (HQ_{idermal}) HQ_{Fe} + HQ_{Mn} + HQ_{Zn} + \cdots$$

Carcinogenic health risk

Regular exposure to elements such as Cd, Pb and Ni may cause potential carcinogenic risk over the lifetime of human. Target cancer risk (TR) was performed to calculate the possible carcinogenic risk from these elements through different pathways (digestion and dermal) following the equation of **USEPA (2011)**.

$$\mathbf{TR = CDI \ x \ CPS_0}$$

Where, CPS_0 is the carcinogenic potency slope of Cd, Pb and Ni (mg/kg bw.day^{-1}). Both TR and total TR (ΣTR) are considered acceptable at 1.0×10^{-6} and 1.0×10^{-5} for a single and multi-carcinogenic aspect **(USEPA, 2010)**.

Fish analysis

Fish were collected from Lake Qarun to represent the three sections of the lake, including the eastern, the middle, and the western sections. A total of ninety adult *T. zillii* and *M. cephalus* (fifteen fish per section of each species), with mean body weight of 50.36 ± 10.15 and 72.43 ± 15.62 g, and body length of 12.26 ± 1.86 and 20.14 ± 22.12cm were collected, respectively. Fish specimens were collected with the aid of local fishermen and kept immediately at -20˚C. Then, specimens of non-edible tissues (liver, kidney and gills) and edible tissues (muscles) were dissected from each fish species to evaluate the heavy metals contents. Fe, Mn, Zn, Cu, Pb, Cd and Ni were estimated in water and different body tissues of both fish according to **APHA (2005)** by the atomic absorption reader (model: GBC Savant with Graphite Furnace 5000).

Metal pollution index (MPI)

The MPI was performed in liver, kidney, gills and muscle tissues from *T. zilli* and *M. cephalus* using **Usero *et al*. (1997)** equation.

$$\mathrm{MPI} = (Cm_{Fe} + \ Cm_{Mn} + \ Cm_{\ldots\ldots\ldots})^{1/n}$$

Where, Cm is the concentration of individual heavy metal in tissue (mg/Kg).

Health hazard assessment for fish consumption

The estimated daily intake of heavy metals (EDI)

EDI was computed for adults according to the pattern of fish ingestion rate (normal and habitual) over life expectancy as specified in the study of **Song *et al*. (2009)**.

$$\mathrm{EDI} = \frac{\mathrm{Mc \ x \ IR}}{\mathrm{BW}}$$

Where, IR is the ingestion rate for normal and habitual consumers (0.031 and 0.14 Kg/day).

Target hazard quotient (THQ)

The THQ is usually applied to evaluate the noncarcinogenic hazard of each ingested metal using the reference dose (R*f*D) of metal cited by **USEPA (2011, 2012)**.

$$\mathrm{THQ} = \frac{\mathrm{EDI \; x \; EF \; x \; ED}}{\mathrm{R}f\mathrm{D \; x \; BW \; x \; AT}n}$$

Where, ATn is the average time for non-carcinogens exposure (365 days/year × ED).

Hazard index (HI)

HI is the total THQ of metals. It expresses the overall health hazard induced by the exposure of more than one metal.

$$\mathrm{HI} = \sum_{i=1}^{n} THQ_{Fe} + THQ_{Mn} + THQ_{Zn} + \cdots$$

Target cancer risk (TR)

TR is achieved to calculate the possible carcinogenic danger associated with the consumption of Cd, Pb and Ni from fish.

$$\mathrm{TR} = \frac{\mathrm{EDI \; x} \; CPS_0 \; \mathrm{x \; EF \; x \; ED}}{\mathrm{AT}c}$$

Where, ATc is the average time for carcinogens exposure (365/year × life expectancy) according to **USEPA (2011)**. TR and ∑TR are considered acceptable at $\leq 1.0 \times 10^{-6}$ **(USEPA, 2010)**.

Statistical analyses

The data of heavy metals in the muscles of *T. zillii* and *M. Cephalus* were expressed by mean ± standard deviation of forty-five fish. Data were statistically investigated using one-way analysis of variance followed by Tukey's test **(Abdi & Williams, 2010)** using GraphPad Instat Version 3.06; the difference between means were considered significant when $P < 0.05$.

RESULTS AND DISCUSSION

Heavy metal in surface water

In the present study, a qualitative comparison was performed between the two specified intervals representing the summer and winter seasons. Great fluctuations were observed in the measured parameters. Results of the IDW analysis revealed that the concentrations of these water chemical parameters increased gradually from the west to the east direction. The entirety of the lake is heavily contaminated by heavy metals; the highest level of pollutants was mainly concentrated in front of the two main drains, and in the western shallow area of the lake.

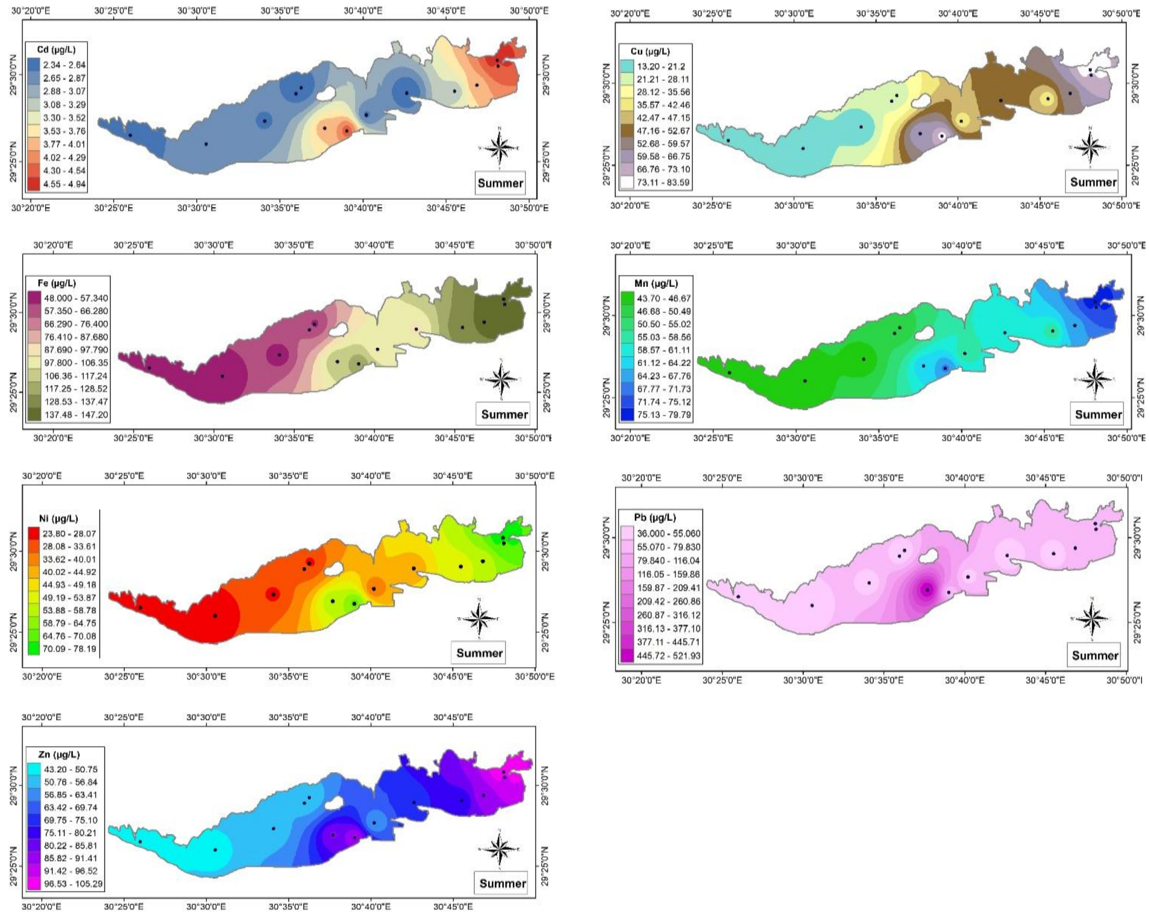

Fig. 2. Spatial variations of the heavy metals (Cd, Cu, Fe, Mn, Ni, Pb, and Zn) as obtained by IDW technique in GIS in summer in µg/L

In both seasons, the eastern section of the lake showed the greatest concentrations of heavy metals. Site (1) had the largest values of all the parameters except Pb, whereas site (8) recorded the greatest Pb concentration in the Lake. Furthermore, the low levels of Cd in the lake were recorded during both seasons. The spatial distribution maps of the water chemical parameters created using IDW interpolation technique in GIS are presented in Fig. (2) for summer measurements and in Fig. (3) for winter measurements.

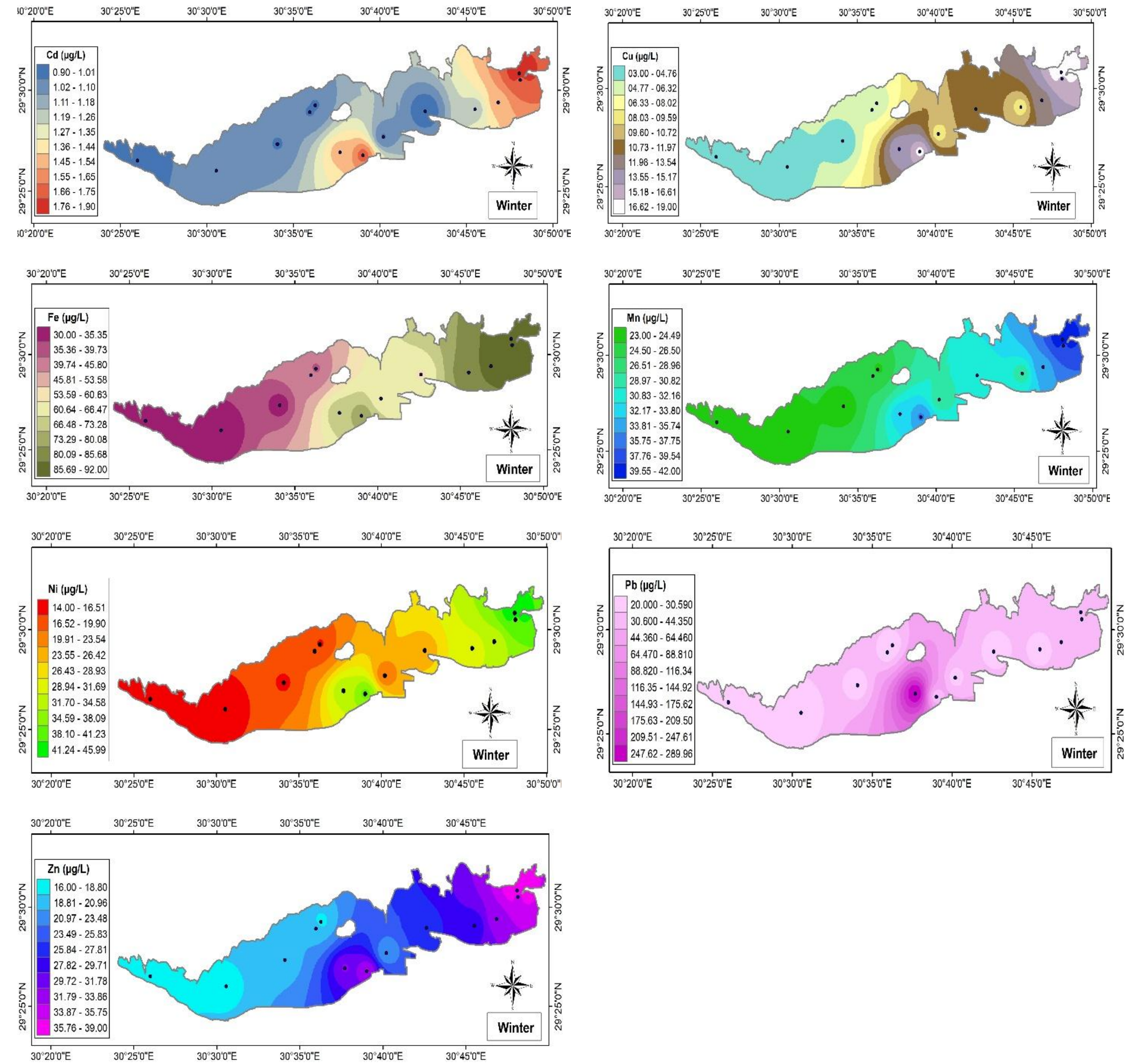

Fig. 3. Spatial variations of the heavy metals (Cd, Cu, Fe, Mn, Ni, Pb, and Zn) in winter in µg/L.

The average concentrations of metals under study in Lake Qarun surface water (µg/L) are demonstrated in Table (1). The highest values of Fe, Mn, Zn, Cu, Pb, Cd and Ni were 92.22, 42.55, 39.47, 19.82, 36.22, 1.95 and 46.19 µg/L; while the lowest levels were 30.10, 23.52, 16.35, 3.61, 20.17, 0.95, and 14.11 µg/L during winter, respectively. Metals recorded an increase in summer, and the highest levels of Fe, Mn, Zn, Cu, Pb, Cd and Ni were 147.14, 79.35,105.84, 83.65, 65.32, 4.91, and 78.36 µg/L; whereas, the lowest levels were 48.62, 43.13, 42.22, 13.82, 36.96, 2.66 and 24.19 µg/L, respectively. Among the studied heavy metals in the present work, Fe, Cu, Zn and Mn were within the standard limits reported by WHO. Conversely, Cd, Pb and Ni were above the drinking water standards documented in **WHO (2017)** with respect to summer. While, Cd and Mn exceeded the WHO guidelines for aquatic life in winter and summer. In water, Fe was the most abundant metal, followed by Zn> Mn> Pb> Ni> Cu> Cd during the study.

The heavy metal evaluation index (HMEI) is generally used to classify and characterize pollutants in water. HMEI in the present study was used to evaluate the surface water in the context of metals load (Table 2).

Table 1. Mean metals concentrations (mean ± S.D µg/L) of Lake Qarun during the study period

Heavy metal	Winter	Summer	*WHO (µg/L)
Fe	61.69 ± 24.10	102.05 ± 38.18	300
Cu	10.0 ±5.61	46.30 ±24.32	2000
Zn	25.15 ±7.86	73.10 ±20.17	3000
Cd	1.26 ± 0.35	3.34 ± 0.92	3
Pb	26.53 ± 5.44	48.85 ±9.44	10
Mn	30.38 ±6.41	59.0 ±11.81	400
Ni	26.61 ± 10.95	46.96 ±18.32	20

***(WHO, 2017)**

Table 2. Calculated heavy metal evaluation index (HMEI) of water samples collected from Lake Qarun

	Winter (HMEI)				**Summer (HMEI)**			
	(Drinking quality)		**(Irrigation quality)**		**(Drinking quality)**		**(Irrigation quality)**	
	Value	**Description**	**Value**	**Description**	**Value**	**Description**	**Value**	**Description**
1	**3.79**	Unfit	0.59	Fit	7.05	Unfit	1.35	Unfit
2	**3.52**	Unfit	0.53	Fit	6.53	Unfit	1.19	Unfit
3	**3.15**	Unfit	0.45	Fit	5.84	Unfit	1.01	Unfit
4	**2.84**	Unfit	0.39	Fit	5.24	Unfit	0.84	Fit
5	**2.37**	Unfit	0.37	Fit	4.36	Unfit	0.83	Fit
6	**2.33**	Unfit	0.33	Fit	4.31	Unfit	0.74	Fit
7	**3.33**	Unfit	0.51	Fit	6.21	Unfit	1.17	Unfit
8	**2.99**	Unfit	0.46	Fit	5.57	Unfit	1.14	Unfit
9	**2.16**	Unfit	0.28	Fit	4.02	Unfit	0.61	Fit
10	**2.04**	Unfit	0.25	Fit	3.81	Unfit	0.55	Fit
11	**2.02**	Unfit	0.24	Fit	3.77	Unfit	0.49	Fit
12	**1.87**	Unfit	0.23	Fit	3.51	Unfit	0.47	Fit
13	**1.8**	Unfit	0.23	Fit	3.42	Unfit	0.48	Fit

The HMEI values for drinking water in winter varied from 1.8 to 3.79 and from 3.42 to 7.05 in summer; while, the HMEI values for irrigation purposes ranged from 0.23 to 0.59 in winter and from 0.47 to 1.35 in summer The HMEI for drinking purpose was rated as “Unfit” for the whole lake during the study, although only five samples out of the thirteen surface water samples collected during summer were characterized as “Unfit” for irrigation usage (Table 2).

The non-carcinogenic health hazards induced by the ingestion and dermal contact of humans with Lake Qarun waters were calculated using hazard quotients (HQ) and hazard index (HI). According to the chronic daily metal intake (CDI) data for ingestion, Fe recorded the highest value followed by Mn> Ni> Pb> Zn> Cu> Cd in winter; while in summer, Fe was followed by Zn> Mn> Pb> Ni> Cu> Cd (Table 3). The mean CDI sequence for the dermal exposure in adults was Fe> Mn> Zn> Cu> Ni> Pb> Cd during the study. In addition, summer recorded higher dermal CDI compared to winter (Table 3).

In winter, the average HQ values due to the ingestion of water obtained in this study were 2.76E-06, 7.85E-06, 2.73E-06, 3.96E-05, 2.78E-04, 2.07E-05, and 4.18E-05 (mg/Kg/Day) for Fe, Cu, Zn, Cd, Pb, Mn, and Ni, respectively (Table 4). The HI mean value of water ingestion during winter was 3.94E-05. Both HQ and HI were higher during summer than in winter. The HQ mean values of Fe, Cu, Zn, Cd, Pb, Mn, and Ni in summer were 4.40E-06, 3.4E-05, 7.41E-06, 1.02E-04, 5.01E-04, 3.95E-05, 7.10E-05, and 7.60E-04 (mg/Kg Day), respectively. While, the mean HI value during summer was 7.60E-04 (Table 5).

Table 3. The average chronic daily metals intake (CDI) due to ingestion and dermal contact (mg/Kg Day) of Lake Qarun waters during the study

Season			Fe	Cu	Zn	Cd	Pb	Mn	Ni
Winter	ingestion	Mean	1.93E-06	3.14E-07	8.21E-07	3.96E-08	8.34E-07	9.54E-07	8.36E-07
		S. D	7.57E-07	1.76E-07	2.47E-07	1.10E-08	1.70E-07	2.01E-07	3.44E-07
	dermal	Mean	1.47E-09	1.47E-10	5.28E-10	5.37E-11	9.77E-11	1.12E-09	1.37E-10
		S. D	1.56E-09	1.95E-10	4.69E-10	4.40E-11	9.77E-11	1.12E-09	1.37E-10
Summer	ingestion	Mean	3.08E-06	1.38E-06	2.22E-06	1.02E-07	1.50E-06	1.81E-06	1.42E-06
		S. D	1.23E-06	7.73E-07	6.60E-07	2.90E-08	3.05E-07	3.79E-07	5.87E-07
	dermal	Mean	2.35E-09	6.45E-10	1.42E-09	1.40E-10	1.76E-10	2.14E-09	2.33E-10
		S. D	2.50E-09	8.60E-10	1.27E-09	1.14E-10	1.76E-10	2.14E-09	2.33E-10

Table 4. The non-carcinogenic human health risks ($HQ_{ingest.}$) and hazard index ($HI_{ingest.}$) of heavy metals in water samples collected from Qarun Lake in winter

	Fe	Cu	Zn	Cd	Pb	Mn	Ni	HI_{ingest}
1	4.13E-06	1.49E-05	4.08E-06	5.97E-05	3.77E-04	2.86E-05	7.22E-05	5.61E-04
2	4.04E-06	1.25E-05	3.66E-06	5.34E-05	3.56 E-04	2.66E-05	6.28E-05	5.1 E-04
3	3.95E-06	1.02E-05	3.45E-06	4.71E-05	3.24E-04	2.39E-05	5.02E-05	4.64E-04
4	3.77E-06	7.07E-06	2.93E-06	3.77E-05	2.93E-04	2.04E-05	4.71E-05	4.12E-04
5	2.69E-06	8.64E-06	2.82E-06	2.82E-05	2.51E-04	2.11E-05	3.92E-05	3.54E-04
6	2.78E-06	7.07E-06	2.2E-06	3.14E-05	2.51E-04	2.04E-05	3.30E-05	3.48E-04
7	3.54E-06	1.33E-05	3.56E-06	5.34E-05	3.35E-04	2.45E-05	6.12E-05	4.95E-04
8	3.23E-06	1.17E-05	3.35E-06	4.71E-05	3.03E-04	2.25E-05	5.34E-05	4.45E-04
9	1.84E-06	4.71E-06	2.09E-06	3.14E-05	2.40E-04	1.77E-05	2.98E-05	3.29E-04
10	1.75E-06	3.92E-06	1.88E-06	3.14E-05	2.30E-04	1.63E-05	2.51E-05	3.11E-04
11	1.48E-06	2.35E-06	1.99E-06	3.14E-05	2.30E-04	1.57E-05	2.51E-05	3.09E-04
12	1.34E-06	2.35E-06	1.88E-06	3.45E-05	2.09E-04	1.57E-05	2.2E-05	2.87E-04
13	1.43E-06	3.14E-06	1.67E-06	2.82E-05	2.09E-04	1.57E-05	2.2E-05	2.82E-04
Mean	2.76E-06	7.85E-06	2.73E-06	3.96E-05	2.78E-04	2.07E-05	4.18E-05	3.94E-04
SD	1.08E-06	4.40E-06	8.23E-07	1.10E-05	5.69E-05	4.37E-06	1.72E-05	9.47E-05

Table 5. The non-carcinogenic human health risks ($HQ_{ingest.}$) and hazard index ($HI_{ingest.}$) of heavy metals in water samples collected from Qarun Lake in summer

	Fe	Cu	Zn	Cd	Pb	Mn	Ni	HI_{ingest}
1	6.60E-06	6.56E-05	1.10E-05	1.55E-04	6.78E-04	5.45E-05	1.22E-04	1.09E-03
2	6.46E-06	5.53E-05	9.9E-06	1.38E-04	6.41E-04	5.06E-05	1.06E-04	1.01E-03
3	6.32E-06	4.49E-05	9.33E-06	1.22E-04	5.84E-04	4.54E-05	8.54E-05	8.98E-04
4	6.03E-06	3.11E-05	7.92E-06	9.80E-05	5.28E-04	3.89E-05	8.01E-05	7.90E-04
5	4.31E-06	3.80E-05	7.63E-06	7.35E-05	4.52E-04	4.02E-05	6.67E-05	6.8 E-04
6	4.45E-06	3.11E-05	5.94E-06	8.17E-05	4.52E-04	3.89E-05	5.61E-05	6.70E-04
7	5.67E-06	5.87E-05	9.61E-06	1.38E-04	6.03E-04	4.67E-05	1.04E-04	9.67E-04
8	5.17E-06	5.18E-05	9.05E-06	1.22E-04	5.46E-04	4.28E-05	9.08E-05	8.69E-04
9	2.94E-06	2.07E-05	5.65E-06	8.17E-05	4.33E-04	3.37E-05	5.07E-05	6.29E-04
10	2.47E-06	1.82E-05	5.35E-06	7.54E-05	4.27E-04	3.19E-05	4.14E-05	6.02E-04
11	2.37E-06	1.03E-05	5.37E-06	8.17E-05	4.14E-04	2.97E-05	4.27E-05	5.87E-04
12	2.15E-06	1.03E-05	5.09E-06	8.98E-05	3.77E-04	2.98E-05	3.74E-05	5.51E-04
13	2.29E-06	1.38E-05	4.52E-06	7.35E-05	3.77E-04	2.98E-05	3.74E-05	5.38E-04
Mean	4.40E-06	3.4E-05	7.41E-06	1.02E-04	5.01E-04	3.95E-05	7.10E-05	7.60E-04
SD	1.75E-06	1.93E-05	2.20E-06	2.90E-05	1.01E-04	8.25E-06	2.93E-05	1.88E-04

Table 6. The non-carcinogenic human health risks (HQ_{dermal}) and hazard index (HI_{dermal}) of heavy metals in water samples collected from Qarun Lake in winter

	Fe	Cu	Zn	Cd	Pb	Mn	Ni	HI_{dermal}
1	1.50E-08	7.74E-08	1.91E-08	9.28E-06	3.38E-07	1.14E-06	8.32E-08	1.10E-05
2	1.47E-08	6.51E-08	1.71E-08	8.31E-06	3.19E-07	1.06E-06	7.24E-08	9.85E-06
3	1.43E-08	5.29E-08	1.61E-08	7.33E-06	2.91E-07	9.50E-07	5.79E-08	8.71E-06
4	1.37E-08	3.66E-08	1.37E-08	5.86E-06	2.63E-07	8.14E-07	5.43E-08	7.06E-06
5	9.77E-09	4.48E-08	1.32E-08	4.40E-06	2.25E-07	8.41E-07	4.52E-08	5.58E-06
6	1.01E-08	3.66E-08	1.03E-08	4.89E-06	2.25E-07	8.14E-07	3.80E-08	6.02E-06
7	1.29E-08	6.92E-08	1.66E-08	8.31E-06	3.01E-07	9.77E-07	7.06E-08	9.75E-06
8	1.17E-08	6.11E-08	1.56E-08	7.33E-06	2.72E-07	8.96E-07	6.15E-08	8.65E-06
9	6.68E-09	2.44E-08	9.77E-09	4.89E-06	2.16E-07	7.06E-07	3.44E-08	5.88E-06
10	6.35E-09	2.04E-08	8.79E-09	4.89E-06	2.07E-07	6.51E-07	2.90E-08	5.81E-06
11	5.37E-09	1.22E-08	9.28E-09	4.89E-06	2.07E-07	6.24E-07	2.90E-08	5.77E-06
12	4.89E-09	1.22E-08	8.79E-09	5.37E-06	1.88E-07	6.24E-07	2.53E-08	6.24E-06
13	5.21E-09	1.63E-08	7.82E-09	4.40E-06	1.88E-07	6.24E-07	2.53E-08	5.26E-06
Mean	1.00E-08	4.07E-08	1.28E-08	6.16E-06	2.49E-07	8.25E-07	4.82E-08	7.35E-06
SD	3.93E-09	2.29E-08	3.84E-09	1.71E-06	5.11E-08	1.74E-07	1.98E-08	1.96E-06

The mean HQ values of dermal exposure to metals in Lake Qarun waters during winter were 1.00E-08, 4.07E-08, 1.28E-08, 6.16E-06, 2.49E-07, 8.25E-07, 4.82E-08, and 7.35E-06 for Fe, Cu, Zn, Cd, Pb, Mn, and Ni, respectively (Table 6). While, the HQ average values during summer for Fe, Cu, Zn, Cd, Pb, Mn, and Ni were 1.60E-08, 1.80E-07, 3.46E-08, 1.59E-05, 4.50E-07, 1.57E-06 and 8.18E-08, individually. Moreover, the mean HI of dermal exposure during winter was lower than that recorded in summer (7.35E-06 and 1.83E-05) (Table 7).

The TR and ∑TR in Table (8) show that, the potential carcinogenic risk from Cd, Pb and Ni of the ingestion and dermal exposures of the lake waters during the study can be considered negligible (TR varied between 10^{-12} and 10^{-6}*):* while ∑TR recorded low carcinogenic risk **(USEPA, 2012)**.

Lake Qarun is suffering from a devastating change due to the continuous flow of drainage water, mainly from irrigation activities and high rates of water evaporation due to climate aridity in the past few years **(Ibrahim & Ramzy, 2013)**. Generally, the amount and quality of the lake's surface water are counting on the climate and natural features of the lake, as well as the anthropogenic activities **(Abu-Ghamja *et al*., 2018; Abd Ellah & Haque, 2022)**.

Among all sampled surface water with respect to heavy metals, Pb and Ni were higher than the maximum permissible limits reported by **WHO (2017)**, while Cd surpassed the WHO standards in summer.

The HMEI was considered to evaluate the seasonal surface water of Lake Qarun for drinking and irrigation purposes in relation to heavy metal contents, which is a very useful index for classifying and assessing pollutants in water **(Singh *et al*., 2017)**. Considering the guideline values of USEPA for drinking water and FAO for irrigation water, data from Lake Qarun recorded that all surface water samples were appraised as inappropriate in the context of drinking water during the study, while samples were identified as appropriate for the irrigation usage in winter, and 61% of the samples collected in summer were suitable.

Evaluation of human health risk embraces the possible effects of the prolonged exposure of pollutants on humans' health. The current study followed the protocol assigned by the **USEPA (2004)** for the possible non-carcinogenic and carcinogenic risks of both ingestion and dermal contacts of surface water from Lake Qarun during winter and summer seasons.

Table 7. The non-carcinogenic human health risks (HQ dermal) and hazard index (HI dermal) of heavy metals in water samples collected from Qarun Lake in summer

	Fe	**Cu**	**Zn**	**Cd**	**Pb**	**Mn**	**Ni**	**HI $_{dermal}$**
1	2.40E-08	3.40E-07	5.14E-08	2.41E-05	6.09E-07	2.17E-06	1.42E-07	2.75E-05
2	2.35E-08	2.87E-07	4.62E-08	2.16E-05	5.75E-07	2.01E-06	1.23E-07	2.47E-05
3	2.29E-08	2.33E-07	4.35E-08	1.91E-05	5.24E-07	1.81E-06	9.84E-08	2.18E-05
4	2.19E-08	1.61E-07	3.69E-08	1.52E-05	4.74E-07	1.55E-06	9.23E-08	1.76E-05
5	1.56E-08	1.97E-07	3.56E-08	1.14E-05	4.06E-07	1.60E-06	7.69E-08	1.38E-05
6	1.62E-08	1.61E-07	2.77E-08	1.27E-05	4.06E-07	1.55E-06	6.46E-08	1.49E-05
7	2.06E-08	3.05E-07	4.49E-08	2.16E-05	5.41E-07	1.86E-06	1.20E-07	2.45E-05
8	1.88E-08	2.69E-07	4.22E-08	1.91E-05	4.90E-07	1.70E-06	1.05E-07	2.17E-05
9	1.07E-08	1.07E-07	2.64E-08	1.27E-05	3.89E-07	1.34E-06	5.84E-08	1.46E-05
10	8.97E-09	9.45E-08	2.50E-08	1.17E-05	3.83E-07	1.27E-06	4.78E-08	1.36E-05
11	8.60E-09	5.37E-08	2.51E-08	1.27E-05	3.72E-07	1.19E-06	4.92E-08	1.44E-05
12	7.82E-09	5.37E-08	2.37E-08	1.40E-05	3.38E-07	1.19E-06	4.31E-08	1.56E-05
13	8.34E-09	7.17E-08	2.11E-08	1.14E-05	3.38E-07	1.19E-06	4.31E-08	1.31E-05
Mean	1.60E-08	1.80E-07	3.46E-08	1.59E-05	4.50E-07	1.57E-06	8.18E-08	1.83E-05
SD	6.38E-09	1.00E-07	1.03E-08	4.52E-06	9.13E-08	3.28E-07	3.38E-08	5.03E-06

Table 8. The target cancer risk (TR) and total TR (ΣTR) values due to ingestion and dermal exposure of heavy metal metals of Lake Qarun water during the study

	Winter						
	ingestion			**Dermal**			**ΣTR values**
	Cd	Pb	Ni	Cd	Pb	Ni	
Mean	1.51E-08	7.09E-09	7.61E-07	2.34E-11	1.28E-08	2.37E-10	1.04E-05
SD	4.18E-09	1.45E-09	3.13E-07	6.50E-12	2.60E-09	9.74E-11	2.86E-07
Min. value	1.19E-08	5.34E-09	1.12E-06	1.67E-11	9.62E-09	1.24E-10	
Max. value	2.27E-08	9.62E-09	9.15E-07	3.53E-11	1.731E-08	4.09E-10	
	Summer						
Mean	3.90E-08	1.28E-08	1.29E-06	6.06E-11	1.99E-12	4.02E-10	1.75E-05
SD	1.10E-08	2.60E-09	5.34E-07	1.72E-11	4.03E-13	1.66E-10	5.25E-07
Min. value	2.79E-08	1.06E-08	1.02E-06	4.34E-11	1.50E-11	2.12E-10	
Max. value	5.90E-08	9.62E-09	9.24E-07	9.17E-11	2.79E-11	6.95E-10	

Cancer risk is considered negligible at $<10^{-6}$: low at $<10^{-5}$: medium at $<10^{-4}$: high at $<10^{-3}$ and very high at $>10^{-3}$

According to the calculated HQ for adult ingestion and dermal contact of surface water, values were below 1.0 during the study, which excludes any adverse health risk all over the lake through both exposure routes during the study. It is worthnoting that, the HQ calculates the potential health hazard of each heavy metal individually; while, the surface water samples contain several metals combined. Therefore, the HI was conducted to calculate the entire possible non-carcinogenic hazards of heavy metals to human health. The calculated HI values for both ingestion and dermal contacts of surface water from Lake Qarun were also less than 1.0 during this study, which implies no possible non-carcinogenic health risks to the inhabitants nearby the lake.

Furthermore, the carcinogenic risk was calculated for the ingestion and dermal exposure of Pb, Cd, and Ni contents in the surface water due to their tendency to affect humans and cause cancers **(Zhang *et al*., 2021**; **Samaila *et al*., 2022)**. The obtained data of target cancer risk (TR) values in Table (8) show that, during winter there is a negligible carcinogenic risk (TR $\leq 10^{-6}$) via both routes of exposure. Whereas, the total TR (ΣTR) recorded low carcinogenic possibilities ($\Sigma TR = 10^{-5}$) to the inhabitants in contact with the lake through the accumulation of heavy metals via both routes of exposure during the study. Generally, the summer season documented more metals contents in surface water samples and higher susceptibility to health risks than winter. Thus, the residents of the study area should be alerted about the potential dangers.

Additionally, the observed fluctuation in the spatial variability maps of the heavy metals created by IDW GIS technique may be attributed to the dilution occurred by drainage water discharged into the lake due to water movement direction. However, the lake has no outlets, it receives pollutants from diverse sources. The water is impacted directly by the discharge of El-Bats drain, which flows into the lake from the eastern side. Whereas, El-Wadi drain discharges into the mid-southern shore of the western basin of the lake **(Authman & Abbas, 2007)**. This leads to the movements of pollutants from the east to the west. Furthermore, it was obvious that location (1) is influenced by the discharge from El-Bats drain in the east, which receives a great amount of agricultural wastewater from the nearby cultivated areas, while site (8) is influenced by El-Wadi drain in the South-middle section of the lake. Furthermore, there are fish-farms and other local drains that discharge their waste waters into the lake **(Authman & Abbas, 2007**).

Heavy metals in fish tissues

The mean metals concentrations in muscles of *T. zillii* and *M. cephalus* are shown in Table (9). Although all metals were higher in both fish tissues than their concentrations in water, all metals in fish edible tissues were within the guidelines of **FAO /WHO (2011)** during winter, except for Pb in *T. zillii*. While in summer, the levels of Pb and Ni in both fish species surpassed the WHO/FAO permissible limits.

The highest residuals of all analyzed heavy metals were detected from the eastern part of Lake Qarun in both *T. zillii* and *M. cephalus* species, followed by the middle part; while in the western part of the lake, fishes showed the lowest metals concentrations.

Among all the studied metals, Fe was the most abundant during the study. In winter, Fe was followed by Zn> Cu> Mn> Pb> Ni> Cd in *T. zillii*, while it was followed by Zn> Cu> Mn> Ni> Pb> Cd in *M. cephalus*. In summer, Fe was the highest accumulated metal in both fishes, followed by Zn> Cu> Mn> Ni> Pb> Cd (**Table 9**). Metal concentrations recorded a significant increase ($P \leq 0.05$) in Fe, Zn, Cd, and Ni from *T. zillii* during summer; however, Cd recorded remarkable variations ($P \leq 0.05$) during the study in both *T. zillii* and *M. cephalus* (Table 9). The highest metal concentrations were recorded in summer for Fe, Cu, Zn, Cd, Pb, Mn, and Ni in *T. zillii* (128.70, 2.89, 26.22, 5.15, 0.91, 0.10, and 2.06 mg/Kg, respectively); while in *M. cephalus*, values were 103.13, 3.13, 19.03, 5.68, 0.33, 0.07, and 125 mg/Kg, respectively.

The bioaccumulation of residual heavy metals in different fish tissues exhibited a tissue and species-specific pattern. Mainly, metal concentrations in different organs of *T. ziilli* were higher, compared to *M. cephalus* during the study.

The target organ of the MPI was liver > gills >kidney> muscles in *T. zillii* during the whole study and in *M. cephalus* only during winter. Nonetheless, the gills of *M. cephalus* recorded the highest MPI during summer, followed by liver> kidney> muscles as shown in Table (10). The MPI of fish from the lake indicates that the highest total metals load was recorded in the eastern section followed by the middle section, whereas the western section showed the lowest MPI (Table 10).

Table 9. Mean metals concentrations (mg/Kg) in *T. zillii* and *M. cephalus* from Lake Qarun

	Winter		**Summer**		**PL**
	T. zillii	***M. cephalus***	***T. zillii***	***M. cephalus***	**WHO/FAO**
Fe	97.28 ± 17.19^{a}	94.84 ± 11.96^{a}	128.70 ± 10.60	103.13 ± 7.57^{a}	425
Mn	2.41 ± 0.41^{a}	2.19 ± 0.11^{a}	2.89 ± 0.53^{b}	3.13 ± 0.36^{b}	500
Zn	16.19 ± 4.03^{ab}	13.08 ± 3.92^{a}	26.22 ± 5.46	19.03 ± 3.92^{b}	99.4
Cu	4.61 ± 1.70^{ab}	4.44 ± 0.46^{b}	5.15 ± 0.79^{ab}	5.68 ± 0.55^{a}	73
Pb	0.86 ± 0.09^{a}	0.23 ± 0.05^{b}	0.91 ± 0.09^{a}	0.33 ± 0.10^{b}	0.3
Cd	0.07 ± 0.02	0.06 ± 0.01	0.10 ± 0.02	0.07 ± 0.01	0.2
Ni	0.66 ± 0.07^{a}	0.58 ± 0.09^{a}	2.06 ± 0.28	1.25 ± 0.30^{a}	1.5

Data were tabulated as mean ± S.D (n=10 fish). Values with different superscripts in a row differ significantly (Tukey Test, $P\leq0.05$). PL: Permissible limits according to the standards of **WHO/FAO (2011)**.

Table 10. Metals pollution index (MPI) in different organs of *T. zillii* and *M. cephalus* from Lake Qarun during the study period

Organ	**Winter**								**Summer**							
	T. zillii				***M. cephalus***				***T. zillii***				***M. cephalus***			
	East	Mid	West	Mean	East	Mid	West	mean	East	Mid	West	mean	East	Mid	West	mean
Liver	7.50	6.50	5.36	6.45	5.85	5.40	4.21	5.15	10.60	9.11	7.41	9.04	6.74	5.85	4.58	5.72
Kidney	4.57	4.43	3.62	4.21	4.08	3.70	3.16	3.65	6.63	6.09	5.00	5.91	4.68	4.15	4.96	4.60
Gills	6.87	6.48	5.53	6.29	5.50	5.04	4.44	4.99	9.87	9.24	7.92	9.01	7.15	6.48	5.43	6.36
Muscles	2.83	2.66	2.01	2.50	2.59	2.32	1.98	2.30	4.15	3.77	3.10	3.67	3.07	2.72	2.26	2.68

The estimated daily intake (EDI) was retrieved for different metals via fish which may induce a human health risk over lifetime (Table 11). Generally, the EDI for normal and habitual consumers of *T. zillii* were higher, compared to those of *M. cephalus*. The EDI of the metals under study in both fish species consumption, covering the whole lake was lesser than the maximum tolerable daily intake (MTDI) documented by **FAO/WHO (2011)** for Zn, Cu, Pb, Cd and Ni (60, 30, 0.2, 0.046 and 0.30 mg/day, respectively). Yet, metals may encourage health risk effects in the future due to the intake of several metals through regular fish consumption over life, and thus an incessant assessment is required.

Table 11. Estimated daily intake (EDI) of metals for adults *via* the consumption of *T. zillii* and *M. cephalus* from Lake Qarun

			T. zillii			***M. cephalus***		
			East	**Mid**	**West**	**East**	**Mid**	**West**
Fe	**Winter**	Normal	5.14E-02	4.24E-02	3.62E-02	4.79E-02	4.17E-02	3.73E-02
		Habitual	2.35E-01	1.94E-01	1.65E-01	2.19E-01	1.90E-01	1.70E-01
	Summer	Normal	6.13E-02	5.87E-02	5.21E-02	4.93E-02	4.61E-02	4.25E-02
		Habitual	2.80E-01	2.68E-01	2.38E-01	2.25E-01	2.10E-01	1.94E-01
Mn	**Winter**	Normal	1.27E-03	1.06E-03	9.00E-04	1.02E-03	9.94E-04	9.23E-04
		Habitual	5.78E-03	4.82E-03	4.11E-03	4.64E-03	4.54E-03	4.21E-03
	Summer	Normal	1.52E-03	1.28E-03	1.06E-03	1.54E-03	1.42E-03	1.23E-03
		Habitual	6.96E-03	5.84E-03	4.82E-03	7.04E-03	6.49E-03	5.59E-03
Zn	**Winter**	Normal	8.83E-03	7.53E-03	5.29E-03	7.26E-03	5.59E-03	4.64E-03
		Habitual	4.03E-02	3.44E-02	2.41E-02	3.31E-02	2.55E-02	2.12E-02
	Summer	Normal	1.41E-02	1.18E-02	9.20E-03	1.00E-02	8.86E-03	6.57E-03
		Habitual	6.42E-02	5.39E-02	4.20E-02	4.57E-02	4.04E-02	3.00E-02
Cu	**Winter**	Normal	1.88E-03	2.88E-03	1.40E-03	2.16E-03	2.01E-03	1.76E-03
		Habitual	8.58E-03	1.32E-02	6.39E-03	9.87E-03	9.19E-03	8.04E-03
	Summer	Normal	2.57E-03	2.42E-03	1.90E-03	2.76E-03	2.56E-03	2.27E-03
		Habitual	1.17E-02	1.11E-02	8.67E-03	1.26E-02	1.17E-02	1.04E-02
Pb	**Winter**	Normal	4.10E-04	4.01E-04	3.39E-04	1.20E-04	1.07E-04	7.58E-05
		Habitual	1.87E-03	1.83E-03	1.55E-03	5.49E-04	4.88E-04	3.46E-04
	Summer	Normal	4.37E-04	4.19E-04	3.61E-04	1.92E-04	1.47E-04	1.07E-04
		Habitual	1.99E-03	1.91E-03	1.65E-03	8.75E-04	6.71E-04	4.88E-04
Cd	**Winter**	Normal	4.06E-05	3.12E-05	2.67E-05	2.90E-05	2.72E-05	2.50E-05
		Habitual	1.85E-04	1.42E-04	1.22E-04	1.32E-04	1.24E-04	1.14E-04
	Summer	Normal	4.90E-05	4.46E-05	3.57E-05	3.25E-05	3.16E-05	2.99E-05
		Habitual	2.24E-04	2.03E-04	1.63E-04	1.49E-04	1.44E-04	1.36E-04
Ni	**Winter**	Normal	3.21E-04	2.99E-04	2.59E-04	2.85E-04	2.72E-04	2.14E-04
		Habitual	1.46E-03	1.36E-03	1.18E-03	1.30E-03	1.24E-03	9.76E-04
	Summer	Normal	1.03E-03	9.36E-04	7.84E-04	6.86E-04	5.62E-04	4.19E-04
		Habitual	4.70E-03	4.27E-03	3.58E-03	3.13E-03	2.56E-03	1.91E-03

The non-carcinogenic risk in this study was conducted through the THQ, which is a valuable risk assessment input related to metal-contaminated food consumption. In this research, the recorded THQ values were less than 1.0 for each metal individually, which proposes that fish are safe for both normal and habitual human consumption patterns (Table 12). Since the THQ considers each metal individually, the THQ cannot be endorsed as a direct assessment of hazard **(USEPA, 1989)**. Furthermore, the HI which is the sum of all metals of THQ; it is considered a risk indicator when it exceeds 1.0. Table (12) records the non-carcinogenic risk for *T. zillii* fish habitual consumers during the study; the habitual *M. cephalus* consumers recorded HI > 1.0 during summer. The HI of the eastern section of the lake displayed the highest HI values, followed by the middle section; whereas, the western section recorded the lowest HI values during the period of investigation.

The target cancer risk originates from the ingestion of food contaminated with Pb, Cd, and Ni, since these metals may pose both carcinogenic and non-carcinogenic risks. The highest TR value of Pb was 1.59E-05 and 4.67E-06 in *T. zillii* and *M. cephalus* during winter for habitual consumers, respectively. Pb in summer recorded higher TR than winter (1.69E-05 and 7.44E-06) for *T. zillii* and *M. cephalus* habitual consumers in summer. The TR of both Cd and Pb in *T. zillii* recorded their highest values in the eastern section of the lake for the habitual consumers (8.50E-05 and 4.28E-03) during summer. On the other hand, the habitual consumers of *M. cephalus* recorded the highest values for Cd and Ni in the eastern section of the lake (5.64E-05 and 2.85E-03) during summer. Generally, summer recorded higher TR than winter. Moreover, the eastern section of Lake Qarun exhibited the highest TR values pursued by the middle section, and the western section showed the lowest value during the study (Table 13).

Considering the USEPA guidelines, TR lesser than 10^{-6} is considered negligible, while TR > 10^{-4} is rated as unacceptable **(USEPA, 1989, 2010)**. The data in Table (13) indicate that the TR of Ni was > 10^{-4}, which is greater than the safe range in all sections of the lake for habitual consumers of both fish during the study, although the normal consumers of both fish recorded TR > 10^{-4} for Ni, which is considered unacceptable values. Meanwhile, Pb and Cd were within the acceptable range (TR> 10^{-6} to 10^{-5}) during the study for both types of consumers and fish species.

The most common route of metal exposure for humans is food ingestion. Malnutrition is a significant problem in low-income and middle-income countries, and fish can efficiently mitigate this burden. Food and nutrition security is an essential multi-dimensional goal in the United Nations Agenda 2030 for Sustainable Development goals (SDGs); it was included in several specific SDGs such as the 2nd goal (Zero hunger) and the 3rd goal (Good Health and Well-Being) **(WHO, 2019)**. Fish contains abundant essential amino acids, many crucial polyunsaturated fatty acids, vitamins, and minerals for humans **(Kawarazuka & Béné 2011; Moxness Reksten *et al*., 2020)**; they can significantly ameliorate FNS, especially in low and middle-income countries, which are more susceptible to hunger and malnutrition.

Fish is a vital component in the Egyptians' diet due to its accessibility and affordability. However, the content of heavy metal in fish tissues was higher by several folds than the threshold levels **(Abdel-Khalek *et al*., 2018)**. Consequently, high rates of fish ingestion can induce many health problems for humans, especially for most coastal inhabitants who consider fish as a major provider of animal protein **(Raknuzzaman *et al*., 2016**; **Liu *et al*., 2018)**. Consequently, *T. zillii* and *M. cephalus* were chosen for the present study due to their dominance in Lake Qarun **(Konsowa, 2006; Shallof, 2020)**.

Generally, the heavy metals contents in both surface water and fish tissues much higher in summer compared to winter. This could be a consequence of higher temperatures which increase the evaporation rates and lower water levels in Lake Qarun **(Ali & Abdel Kawy, 2013)**. Moreover, the microbial activity in the sediment increases during summer; it enhances the liberation of heavy metals and degradable organic matter from the underlying sediments **(Kowalski *et al*., 2009)**.

Table 12. Target hazard quotient (THQ) and hazard ndex (HI) of metals for adults via the consumption of *T. zillii* and *M. cephalus* from Lake Qarun

Heavy metal	Season		*T. zillii*			*M. cephalus*		
			East	Mid	West	East	Mid	West
Fe	Winter	Normal	0.073	0.061	0.052	0.068	0.060	0.053
		Habitual	0.335	0.277	0.236	0.312	0.272	0.243
	Summer	Normal	0.088	0.084	0.074	0.070	0.066	0.061
		Habitual	0.400	0.383	0.340	0.321	0.301	0.277
Mn	Winter	Normal	0.009	0.006	0.005	0.006	0.006	0.005
		Habitual	0.041	0.028	0.024	0.027	0.027	0.025
	Summer	Normal	0.011	0.008	0.006	0.009	0.008	0.007
		Habitual	0.050	0.034	0.028	0.041	0.038	0.033
Zn	Winter	Normal	0.029	0.025	0.018	0.024	0.019	0.015
		Habitual	0.134	0.115	0.080	0.110	0.085	0.071
	Summer	Normal	0.047	0.039	0.031	0.033	0.030	0.022
		Habitual	0.214	0.180	0.140	0.152	0.135	0.100
Cu	Winter	Normal	0.047	0.072	0.035	0.054	0.050	0.044
		Habitual	0.215	0.329	0.160	0.247	0.230	0.201
	Summer	Normal	0.064	0.061	0.047	0.069	0.064	0.057
		Habitual	0.293	0.277	0.217	0.315	0.292	0.259
Pb	Winter	Normal	0.137	0.134	0.113	0.040	0.036	0.025
		Habitual	0.624	0.610	0.515	0.183	0.163	0.115
	Summer	Normal	0.146	0.140	0.120	0.064	0.049	0.036
		Habitual	0.665	0.637	0.549	0.292	0.224	0.163
Cd	Winter	Normal	0.041	0.031	0.027	0.029	0.027	0.025
		Habitual	0.185	0.142	0.122	0.132	0.124	0.114
	Summer	Normal	0.049	0.045	0.036	0.033	0.032	0.030
		Habitual	0.224	0.203	0.163	0.149	0.144	0.136
Ni	Winter	Normal	0.016	0.015	0.013	0.014	0.014	0.011
		Habitual	0.073	0.068	0.059	0.065	0.062	0.049
	Summer	Normal	0.051	0.047	0.039	0.034	0.028	0.021
		Habitual	0.235	0.214	0.179	0.157	0.128	0.096
Hazard Index (HI)								
Winter		Normal	0.35	0.34	0.26	0.24	0.21	0.18
		Habitual	1.61*	1.57*	1.20*	1.08*	0.96	0.82
Summer		Normal	0.46	0.42	0.35	0.31	0.28	0.23
		Habitual	2.08*	1.93*	1.62*	1.43*	1.26*	1.06*

* HI≤1.0

Table 13. The Target cancer risk (TR) and total cancer risk (∑TR) of metals for adults via the consumption of *T. zillii* and *M. cephalus* from Lake Qarun

Heavy metal	Season		*T. zillii*			*M. cephalus*		
			East	Mid	West	East	Mid	West
Pb	Winter	Normal	3.49E-06	3.41E-06	2.88E-06	1.02E-06	9.09E-07	6.44E-07
		Habitual	1.59E-05	1.56E-05	1.31E-05	4.67E-06	4.15E-06	2.94E-06
	Summer	Normal	3.71E-06	3.56E-06	3.07E-06	1.63E-06	1.25E-06	9.09E-07
		Habitual	1.69E-05	1.63E-05	1.40E-05	7.44E-06	5.71E-06	4.15E-06
Cd	Winter	Normal	1.54E-05	1.19E-05	1.02E-05	1.10E-05	1.03E-05	9.48E-06
		Habitual	7.03E-05	5.41E-05	4.64E-05	5.02E-05	4.72E-05	4.33E-05
	Summer	Normal	1.86E-05	1.69E-05	1.35E-05	1.24E-05	1.20E-05	1.13E-05
		Habitual	8.50E-05	7.73E-05	6.18E-05	5.64E-05	5.49E-05	5.18E-05
Ni	Winter	Normal	2.92E-04	2.72E-04	2.35E-04	2.60E-04	2.47E-04	1.95E-04
		Habitual	1.33E-03	1.24E-03	1.07E-03	1.18E-03	1.13E-03	8.89E-04
	Summer	Normal	9.37E-04	8.52E-04	7.14E-04	6.25E-04	5.11E-04	3.81E-04
		Habitual	4.28E-03	3.89E-03	3.26E-03	2.85E-03	2.33E-03	1.74E-03
∑TR	Winter	Normal	3.11E-04	2.87E-04	2.48E-04	2.72E-04	2.59E-04	2.05E-04
		Habitual	1.42E-03	1.31E-03	1.13E-03	1.24E-03	1.18E-03	9.35E-04
	Summer	Normal	9.59E-04	8.72E-04	7.30E-04	6.39E-04	5.24E-04	3.94E-04
		Habitual	4.38E-03	3.98E-03	3.33E-03	2.91E-03	2.39E-03	1.80E-03

Cancer risk is considered negligible at $<10^{-6}$: low at $<10^{-5}$: medium at $<10^{-4}$: high at $<10^{-3}$ and very high at $>10^{-3}$

In addition, the eastern section of Lake Qarun recorded the highest heavy metals load in surface water and fish samples, compared to the other two sections of the lake. This may be attributed to the impact of El-Batts drain, which is the biggest drain at the lake, besides the heavy anthropogenic activity in this section of the lake **(Abdel-Khalek *et al*., 2020)**. Alternatively, *T. zillii* has greater tendency to collect heavy metals than *M. cephalus*.

Rajeshkumar and Li. (2018) postulated that heavy metals accumulate in fish tissues according to a pattern that is significantly affected by the location, species, and tissue origin. In agreement with the current findings **Abdel-Khalek *et al*. (2020)** reported the same pattern of metals accumulation in the lake's water and different fish species from Lake Qarun. The previous study detected a significant reduction of water dissolved oxygen at the eastern section of the lake due to the breakdown of organic materials that flux into this section. In hypoxic conditions, fish increase their respiration rate, which in turn, upsurges the entry and accumulation of heavy metals into the fish body **(Mansour & Sidky, 2003)**.

The MPI was applied to identify the capacity of each organ to accumulate heavy metals. The present data revealed that active metabolic tissues have higher metals contents. These findings concur with those of **Salaah and El-Gaar (2020)** who documented that, the metabolic active organ such as liver has higher capacity to accumulate metals, compared to other organs owing to the action of particular metal-binding proteins and coenzyme-catalyzed reactions **(Dikanović *et al*., 2016)**. Additionally, gills of both fish species showed a remarkable metal content, which may be attributed to the +ve charge and the thick layer of mucus on its surface, which facilities the absorption of metals, besides being directly exposed to the surroundings. Fortunately, the edible part of fish (muscles) recorded the lowest MPI in both fish species, which may be correlated to its limited metabolic activity and content of metal binding proteins **(Moussa *et al*., 2022)**.

The assessment of the possible human health hazards related to the contents of heavy metals in consumable fish tissues was the key objective of the present study. Human health evaluation standards are based on contaminant intake, as well as exposure rate and extent, average body weight and consumption rate **(Khalil *et al*., 2017)**. While, each metal poses a low health hazard; the edible fish tissue comprises a bulk of metals, which can cause an adverse health effect on humans. Regarding these criteria, the present HI levels are away from posing a health hazard to normal consumers; however, habitual customers are exposed to potential non-carcinogenic health effects (HI$\leq$1.0), associated with both fish species from Lake Qarun.

According to USEPA risk guidelines, Ni recorded the highest lifetime cancer risk for both types of consumers of *T. zillii* and *M. cephalus* fish from Lake Qarun during the study, especially for habitual consumers. The total cancer risk ($\sum$TR) induced by consuming *T. zillii* and *M. cephalus* indicates high and very high risk for normal and habitual consumers, respectively. *T. zillii* displayed a higher cancer risk than *M. cephalus*. Concerning the ∑TR data, *T. zillii* consumption may induce cancer cases, varying between two to three per ten thousand normal consumers, and one per thousand of habitual adult consumers during winter, respectively. In summer, the potential cancer cases were higher, it varied from seven to nine cases per ten thousand and three to four per thousand normal and habitual adult consumers, correspondingly.

On the other hand, the potential cancer risk from the normal ingestion of *M. cephalus* from the lake recorded two possible cancer cases per ten thousand consumers, and varied between four to six cases per ten thousand for adult consumers during winter and summer, separately. Moreover, the habitual consumption of *M. cephalus* documented higher possible cases, which ranged from nine per ten thousand and one case per thousand adult consumers during winter, and from one to two per thousand during summer.

CONCLUSION

The present study demonstrates the importance of assessing the total human health risk induced by heavy metal contamination. The current data recorded possible non-carcinogenic risk from self-independent fish consumers, especially during the summer, as well as potential high carcinogenic risk due to Ni contamination in the edible tissues of both fish *T. zillii* and *M. cephalus* (especially *T. zillii*) from Lake Qarun with a significant alert for habitual fish consumers. Therefore, both inhabitants and fishermen in the study area should be forewarned about the accumulative potential health risks from surface water and consuming fish from Lake Qarun since they are exposed to all routes of exposure. Furthermore, the eastern part of the lake is highly influenced by the discharge of wastewater than the other parts. Therefore, there is an urgent need for a proper treatment of wastewaters before it inters the lake to decrease the contamination load and associated health risks.

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