Original article

Comprehensive environmental assessment of heavy metal contamination of surface water, sediments and Nile Tilapia in Lake Nasser, Egypt

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A R T I C L E   I N F O

A B S T R A C T

Heavy metals cause deleterious effects on human health and drastically alter the biogeochemical cycles within freshwater habitats. The main human activities leading to heavy metal contamination of various aquatic ecosystems comprise the industry, agriculture, urbanization, transport and mining. Lake Nasser is the main freshwater source in Egypt, usually polluted from upstream human activities from the hydrographic basin of the River Nile. The current study surveyed the impact of heavy metals contamination (i.e., Cd, Zn, Pb and Cu) in water, sediment and two Nile Tilapia (*Oreochromis niloticus*) fish organs (liver and muscles) at six sampling sites along Lake Nasser. Additionally, the effects of heavy metals bioaccumulation in the aquatic ecosystem, via water, sediments and fish organs were investigated. The conclusion is that the water of Lake Nasser is safe for use in terms of human consumption, agricultural utilization and public sanitation.

1. Introduction

Lake ecosystems comprise inland water bodies that lack any direct exchange with oceans and share many ecological and biogeochemical processes that are commonly within the classic framework definition of limnology (Bhateria and Jain, 2016).

Any alteration in lakes' environmental status or water quality will inadvertently impact not only the water body *per se*, but equally the human population from adjacent areas (Hedfi et al., 2013). The human usage of lake waters, such as for drinking water supply, irrigation, fishing and clean-energy generation impact the worldwide economics, including the one of Egypt (Duan and Bastiaanssen, 2015).

Lake Nasser was formed in 1964 following the construction of the Aswan High Dam in Upper Egypt. Aswan High Dam was constructed for several purposes, such as for water storage given adequate water input along the year, to overcome floods and for clean energy (i.e. hydropower) generation. Lake Nasser is the largest source of freshwater in Egypt accounting for about 95% of the total Egyptian freshwater budget (Rizk et al., 2020). The lake is about 300 km long and represents the world's largest embankment dam (Abd Ellah, 2020). This lake is very important for the economy of Egypt, given the absence of the appreciable rainfall regime and the agriculture dependence entirely on irrigation (Rizk et al., 2020). Hence, the need for appropriate monitoring techniques to be implemented in order to check the water quality on a regular basis is of primary importance.

Among various types of pollutants, heavy metals are of major concern, given not only the wide array of compounds with multi-faceted effects on lake ecosystems, but equally their various input

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pathways, such as the bedrock weathering, hydrodynamic processes and atmospheric deposition. The government administration of Aswan region restricted severely the use of agricultural fertilizers, discharge of household and industrial wastewater (Ideriah et al., 2012). Therefore, the main source of heavy metals in Lake Nasser comprises mainly the suspended organic matter boosted by floodwaters and those generated by improper land use along River Nile hydrographic basin, particularly in Ethiopia (Farhat and Aly, 2018). The sedimentation of suspended organic matter, to which heavy metals are intimately bound, is a complicated process, usually increasing significantly in reservoirs. The high sedimentation rates in this lake represent a very serious environmental and economic issue that must be sorted out in a sustainable manner. The main source of sediments comes from the highlands, where the erosion processes carry them downstream via the river straight into the lake. Most of the deposited sediment on the bottom of the lake comprises silt, with some traces of sands (ElKobtan et al., 2016). The heavy metals in aqueous solution do not always exhibit direct toxic effects on the environment; instead, they tend to (bio) accumulate and to persist in the environment. Moreover, these compounds are not biodegradable and cause detrimental effects on the environment and human health (Ntakirutimana et al., 2013). Several techniques were developed in time to assess the heavy metal effects bound to sediments, such as the geological accumulation index (Imam et al., 2020), sediment enrichment agent, contamination factor and degree of contamination.

Historically, the worldwide fish consumption increased directly with the interest in its nutritional value, mainly as a source of valuable proteins. Dietary guidelines in the United Kingdom recommend the consumption of fish and fish-based products at least twice a week to meet the daily requirements of polyunsaturated fatty acids (Clonan et al., 2012). Given that fish fill upper positions within aquatic food webs, the heavy metals can bioaccumulate in their biomass via food, water and sediments in significant amounts (Zhao et al., 2012), with direct toxic effects to humans (Castro-González and Méndez-Armenta, 2008). The human contamination with heavy metals via fish consumption leads sometimes to liver and kidney failures and cardiovascular diseases, to name just a few of the induced detrimental health effects.

This led to the implementation of numerous international screening approaches with the aim of estimating the quality of fish meat, as well as to survey the health of aquatic ecosystems (Meche et al., 2010). Essential metals, such as zinc and copper fulfill important physiologic roles; however, their bioaccumulation beyond certain thresholds becomes highly toxic for humans. Non-essential metals, such as lead, cadmium and mercury are nonetheless extremely dangerous for both humans and environment (Bawuro et al., 2018). These non-essential metals bioaccumulate in any given organism, leading to tissue damages, followed by a wide series of disorders and significant toxic effects along food webs. Heavy metals are non-biodegradable and once released in aquatic habitats, they are absorbed into sediment or accumulate in biota. Usually, the fish are more prone to accumulate significant amounts of heavy metals from water and food in various tissues (Weber et al., 2013). Moreover, they absorb significant concentrations of heavy metals even when their amount in aqueous form is below the detection limit of routine chemical analyses (Imam et al., 2020). Therefore, various fish organs represent important targets for properly assessing the health of the aquatic environment from this perspective. The accumulation rate of heavy metals such as lead, zinc, copper and cadmium in several tissues of the iconic fish Nile Tilapia (*Oreochromis niloticus*) from Lake Nasser was previously investigated (Rashed, 2001). The main findings of these studies were that these heavy metals are cycled within the lake ecosystem along with the energy and nutrients flows through food webs. However, most of these studies rather focused on one compound at a time, therefore precluding their synergic interactions within both the lake ecosystem and within fish tissues, despite a general acknowledgment of this information gap. Therefore, in the current study, we tried to fulfill this knowledge gap through a holistic investigation of the distribution of these heavy metals in water, sediment, and fish in Lake Nasser, as well as through assessing their accumulation rates in various fish organs. To understand the ecological risk related to heavy metal contamination, we calculated the metal pollution index (MPI). The MPI provides comprehensive information about the metal toxicity in a particular sample and offers an understanding of the quality of the aquatic environment. The current study comprises a continuation of previous ecotoxicological investigations carried in Lake Nasser (Rizk et al., 2020).

2. Materials and methods

2.1. Study area

Six sites were carefully selected within the main channel of Lake Nasser for water sampling, fish catching and sediment collection, starting from site Abu-Simbel (1) in the south, followed by Armina (2), Tushka (3), Korosko (4), Kalabsha (5) and High Dam site (6) situated in the northern part of the lake (Fig. 1).

2.2. Sampling procedures

2.2.1. Water samples

Water samples were collected in polyethylene bottles (2 L) according to Cornell et al. (2016). The samples were acidified with nitric acid to prevent organic matter alteration by bacterial activity and transferred in an ice-box to the laboratory of Botany Department, Faculty of Science of Port Said University.

2.2.2. Sediment samples

Three replicates of sediments were collected with the aid of an electronic vibrational core sampler tube (vibracorers), which enables sampling efficiently to a depth of eight meters (USGS, 2005). Following the packing of sediment samples in polythene bags and chilled in an ice box, they were transported to the laboratory for further analysis. The samples were dried overnight at 105 °C to constant weight for heavy metal analysis.

2.2.3. Fish samples

Nile Tilapia (*Oreochromis niloticus*) is a native fish species to Egypt and one of the most common fish used in the Egyptian cuisine and in fisheries in Aswan governorate. A total of 30 individuals were collected by local fisherman in March 2019.

2.3. Sample preparation

2.3.1. Water samples

The concentration of heavy metals in water samples was measured according to APHA (2012) standards, with the aid of an Atomic Absorption Spectrophotometer (AAS).

2.3.2. Sediment samples

The digestion of sediment was performed based on USEPA (2010) standards. Fifteen mL of concentrated HNO_3, HF and $HClO_4$ were mixed into a Teflon beaker with 0.5 g of sediment. The samples were sealed afterwards with a lid and kept for 3 h at room temperature, then evaporated until they turned into a liquid solution. Following that, 5 ml of $HClO_4$ was added and vaporized to drought. Concentrated HCl (10 ml) was added to samples and
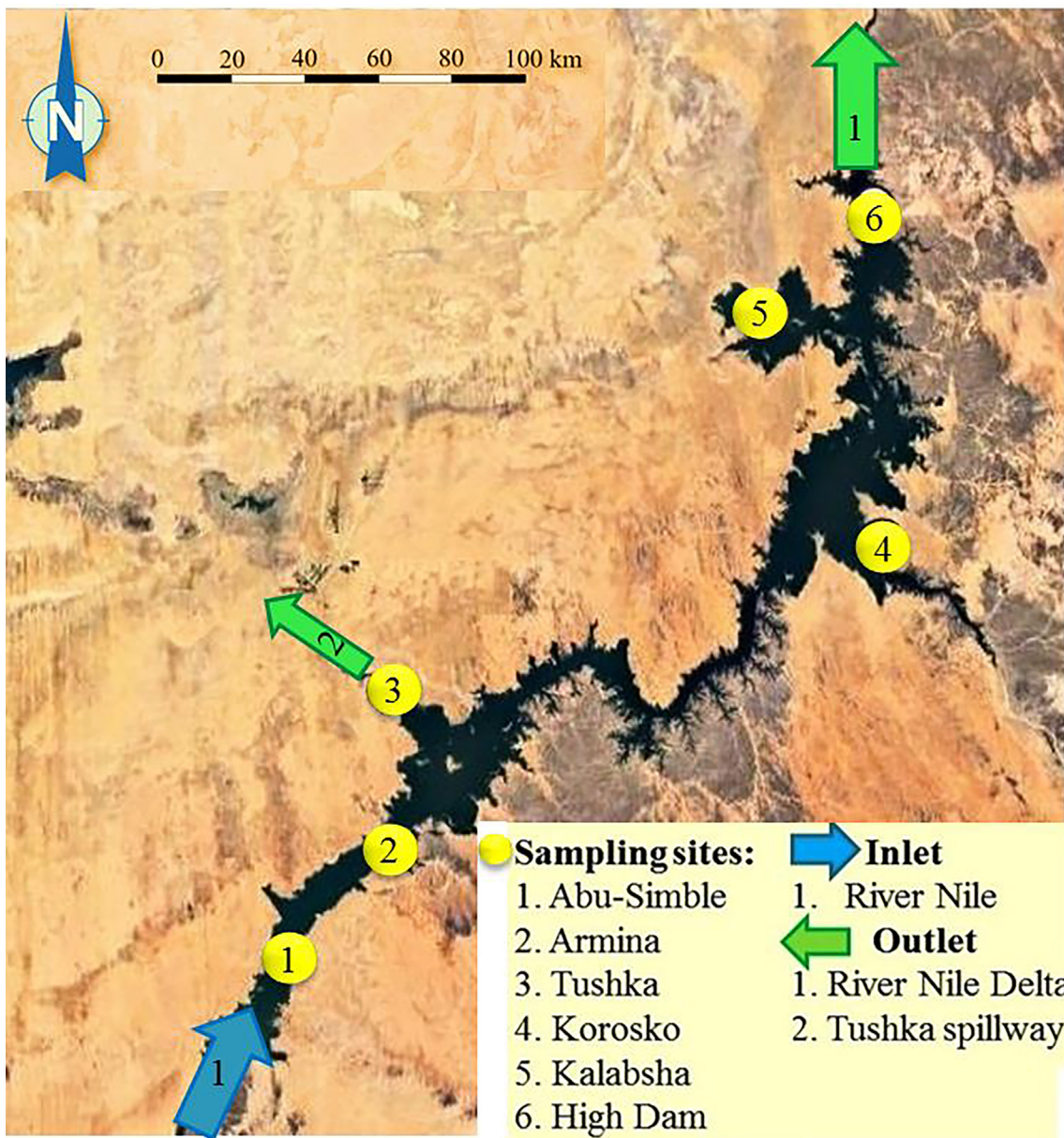
Fig. 1. Sampling sites and main water supplies/inlets and discharge/outlet points of Nasser Lake.

placed back on a hot plate until the solution became clear. Then, it was filtered and supplemented with deionized water up to 100 ml in a volumetric flask.

2.3.3. Fish samples

Various fish organs were extracted through dissection. Muscle and liver organs were removed and their preparation for the measurement of heavy metals was carried according to Hlavay (1996). Therefore Cd, Cu, Pb and Zn contents were measured according to Krishnamurty et al. (1976). First, the samples were dried and then digested on steam bath at approximately 80 °C for 3 h, followed by the addition of 14 ml of concentrated HNO_3 and 7 ml of 30 % H_2O_2, in this order. All samples were diluted to 50 ml with ultra-distilled water and stored in polyethylene containers at room temperature until further measurements.

2.4. Atomic Absorption spectroscopic measurement

Heavy metal concentrations were measured with the aid of an AAS (Model ICE series 3000 AAS) with a GF 5000 graphite furnace in water, sediment and fish samples. In case of fish samples, the precision of the analytical procedure was checked by using standard reference materials (dogfish muscle (DORM 4) and liver (DOLT 5) Canadian Research Council) in five replicates. The precision of analysis was calculated according to Farkas et al. (2007).

2.5. Metal pollution index (MPI)

To assess the metal pollution, the metal pollution index (MPI) was used according to (Abdel-Khalek et al., 2016) using the following equation:

$MPI = (CM_1 \times CM_2 \times \dot{CM_3} \times \cdots \cdots \times CM_n)^{1/n}$ Where, CM_1 is the concentration value of first concerned metal, CM_2 is the concentration value of second concerned metal, CM_3 is the concentration of third concerned metal and CM_n is the concentration of n_{th} metal (mg/kg dry wt) in the tissue sample of a certain samples.

2.6. Model evaluation

In this study, a comprehensive evaluation method was used to evaluate the correlation between the contamination with heavy metals and sample types (i.e., water, sediment, liver and muscles) of investigated items. The main evaluation indexes included the coefficient of determination (R^2), and Pearson correlation coefficient (Corr).

3. Results and discussion

Lake Nasser is the largest source of freshwater in Egypt. However, there are no point pollution sources with heavy metals in its hydrographic basin. The lake receives heavy metals via anthropogenic activities, such as fishing activities, sewage pollution, fishing boats and cruise ships, as well as others which are disposed off in wastes directly into the Sudanese main stem of River Nile (Darwish, 2013). The copper, zinc, lead and cadmium were selected in this study according to the recommendations of Egyptian Water Administration. High concentrations of copper and zinc are needed, as opposed to lead and cadmium which require low dosages, to cause severe environmental and human health issues. Humans are exposed to these heavy metals via consumption of water and fish, which bioaccumulate in various tissues, leading to both acute and chronic intoxications.

3.1. Heavy metals concentrations in water

Table 1 presents the mean concentrations of heavy metals dissolved in water in the six sampling sites of Lake Nasser. Which were below the limits imposed by the Egyptian Governmental Decree No. 92/2013 (GD, 2013) and by environmental quality standards (EQS, 2008) (Directive 2008/105/EC) of European Union, as well as by the aquatic life suitability standard of Canada (CCME, 2007).

Sites 3 and 6 exhibited the highest heavy metal concentrations, whereas the site 1 showed the lowest. The measured values of heavy metals from the current study were compared to those from different countries in Table 2. In comparison with the registered heavy metal concentrations in various worldwide lakes, it can be concluded that the heavy metal concentrations in Lake Nasser are in fact significantly lower compared to Kenya (Outa et al., 2020), China (Jiang et al., 2018), USA (An and Kampbell, 2003), Lake Constance (Petri, 2006), Lake Geneva (La CIPEL, 2015) and Lake Balaton (Nguyen et al., 2005).

3.2. Assessment of environmental prominence of minerals in sediment stores in comparison to SQGs

Table 3 summarizes the measured values of heavy metals in sediment and compares them to quality guideline values, which comprise the minimum critical concentrations, which is represented by the toxic effect threshold (TET). The concentration of copper varies between 13 and 21.8 $\mu g.g^{-1}$; high concentrations were recorded at site 3 (21.8 $\mu g.g^{-1}$), followed by the site 6 (21 $\mu g.g^{-1}$). However, the lowest copper concentration was recorded at site 1 (13 $\mu g.g^{-1}$). The concentrations of zinc were high in all investigated sampling sites. To determine the state of metal pollution, the Sediment Quality Guidelines (SQGs) were applied as reference. SQGs were derived from the sediment quality pollutant concentrations using Chemical and Biological Impact Database (Jones et al., 1997; USEPA, 1999).

However, the usage of SQGs simultaneously with municipal data requires caution. This is important especially in the risk evaluation of heavy metal loads from sediment samples. The recorded values are well correlated with the water flow along a south to north latitudinal gradient. In conclusion, the sediment from Lake Nasser can be considered safe for agriculture activities as well as for aquatic biota (Imam et al., 2020).

3.3. Heavy metal concentrations in fish organs

Fish length and net body weight were ranged between 21.5 and 32.8 cm and 225.5–500.5 g in weight, respectively (Table S1).

Table 4 shows the concentrations of Cu, Zn, Cd and Pb in fish muscles compared to the standards of heavy metal levels of the European Community (EC, 2005), Food and Agriculture Organization (FAO, 2012), FAO/WHO limits (FAO/WHO, 2011), World Health Organization (WHO, 1989) and Ministry of Agriculture, Fisheries and Food of UK (MAFF, 2000). The copper concentrations varied between 1.2 $\mu g.g^{-1}$ at site 1 to 9.17 $\mu g.g^{-1}$ at site 3. The zinc concentrations exhibited the highest concentration (15.70 $\mu g.g^{-1}$) at site 3 and the lowest (8.5 $\mu g.g^{-1}$) at site 1.

The cadmium concentrations recorded the lowest concentrations (0.15 $\mu g.g^{-1}$) at sites 1 and 2. In site 3 agriculture activities affect water quality, influencing directly water and sediment dwelling biota.

Table S2 shows the concentrations of cadmium, zinc and lead which are within the certified limits of standard samples. Regarding copper, both standard fish samples (DORM 4 and DOLT 5) were below certified values and within acceptable limits (96.11 % confidence level). Table S3 presents the concentrations of heavy metals in fish liver. The highest heavy metal concentrations (Cu, Zn and Cd) in fish liver were measured at site 6, in the northern part of the lake (28.90, 58.10 and 0.50 $\mu g.g^{-1}$, respectively) whereas the lowest values were recorded at site 1, in the southern part of the lake (Cu: 13.80, Zn: 37.50 and Cd: 0.3 $\mu g.g^{-1}$ respectively). The low-

Table 1
Concentration of Heavy metals in Lake Nasser and national and international guideline limit values according to various standards.

Heavy metal concentrations ($\mu g.L^{-1}$)	Measuring sites in Lake Nasser						limit values, $\mu g/L$		
	1	2	3	4	5	6	[a]EG (GD 2013)	[b]EQS	[c]CCME, 2007
	Abu-Simble	Armina	Tushka	Korosko	Kalabsha	High Dam			
Cu	0.80	2.68	6.700	2.67	1.98	4.70	10	10	4.00
Zn	7.13	7.56	11.80	7.66	9.00	9.11	10	10	50.00
Cd	0.025	0.025	0. 065	0.03	0.03	0.06	1.0	≤0.08	1.00
Pb	0.01	0.02	0.040	0.03	0.03	0.04	10	1.2	10.00

[a] EG (GD 2013) Egyptian Governmental Decree No. 92/2013.
[b] EQS, 2008 (Environmental Quality Standards in the Field of Water Policy, Directive 2008/105/EC).
[c] CCME, 2007 (Canadian Council of Ministers of the Environment For the Protection of Aquatic Life).

Table 2
Global overview of mean heavy metals concentrations in water of different water bodies in different countries.

Lake Location /concentration (μg element.L^{-1})	Pb	Cd	Zn	Cu	References
Nasser Lake	0.028	0.039	8.70	3.26	current study
Constance Lake (Germany, Switzerland and Austria)	0.050	0.250	1.500	1.100	Petri (2006)
Baikal Lake (Russia)	1.5	7	1–5	1	Shiretorova et al. (2020)
Vemband Lake (India)	3.94	1.63	74.93	7.31	Shylesh Chandran et al. (2019)
Caizi Lake (China)	2.42	0.12	34.33	2.54	Jiang et al. (2018)
LosMolinos Lake (Argentina)	0.07	–	3.75	0.67	Griboff et al. (2018)
Geneva Lake (shared between Switzerland and France)	<0.050	0.005	–	0.770	La CIPEL (2015)
Lake Balaton (Hungary)	0.040	0.002	0.970	0.460	Nguyen et al. (2005)
Lake Texoma, Oklahoma–Texas (USA)	<15	20	59	24	An and Kampbell (2003)
Lake Victoria (Kenya)	1.054	0.070	144	1.568	Outa et al. (2020)
Lake Victoria (Mwanza and Winam Gulfs)	22–823	0–70	18–50	–	Ogoyi et al. (2011)
Tana Lake (Ethiopia)	3–6	30–60	110–160	110–150	Brihanu (2016)
Tanganyika Lake (Tanzania)	7–120	< 10.00	10.00	< 6.00	Chale (2002)

Table 3
Heavy metals concentrations in sediment of Lake Nasser and sediment quality guidelines for selected heavy metals.

Elements concentrations (mg.kg^{-1})	Measuring sites/heavy metal concentrations alongside Lake Nasser						*SQG				
	1	2	3	4	5	6	[a]TEC	[b]PEC	[c]PEL	[d]SEL	[e]TEL
	Abu-Simble	Armina	Tushka	Korosko	Kalabsha	High Dam					
Cu	13.00	15.80	21.80	18.00	18.00	21.00	31.0	149	197	110	86
Zn	19.00	25.00	45.00	30.00	38.00	40.00	121	459	315	820	540
Cd	0.165	0.178	0.35	0.27	0.31	0.356	0.99	4.98	3.53	10.0	3.00
Pb	0.95	2.00	3.00	2.00	2.00	3.00	–	128	91	250	170
MPI	2.49	3.44	5.57	4.16	4.54	5.23					

*SQG: Sediment quality guideline (Jones et al., 1997; USEPA, 1999).
[a] TEC: Threshold effect concentration (MacDonald et al., 2000).
[b] PEL: Probable effect level for dry weight (USEPA, 1999).
[c] SEL: Severe effect level for dry weight (Persaud et al., 1992).
[d] TET: Toxic effect threshold for dry weight (MacDonald et al., 2000).
[e] PEC: Probable effect concentration (MacDonald et al., 2000).

est lead concentration was recorded at site 2 (0.1 μg.g^{-1}) and the highest at site 3 (2.1 μg.g^{-1}).

3.4. Heavy metal distributions among Lake Nasser

Heavy metals distribution along the lake offers a better understanding of the level of lake contamination (Hasimuna et al., 2021). This way, the contamination with heavy metals and where the highest concentrations are to be expected is much better represented. An overall picture as this may help authorities to draw people's attention to the potential risk of heavy metal contamination (Turan et al., 2020). Such mapping can help with proper implementation of preventive measures. However, it is necessary to emphasize the fact that currently there are no heavy metal contamination sources in Lake Nasser hydrographic basin, providing a solid basis

for the future development of agricultural activities in the region and efficient water management in Egypt.

3.4.1. Copper

Copper content in water, sediment and both fish muscle and liver has represented in Fig. 2. It highlights the lowest copper concentrations with blue, which is the best water quality in terms of contamination with this heavy metal, whereas the yellow highlights indicate high concentrations. The decreasing copper concentrations in studied samples are in liver > sediment > muscle > water. Sediment and liver samples exhibited higher concentrations in the lake (13–21.8 and 13.8–28.9 mg.kg^{-1} respectively), supporting the hypothesis of its bioaccumulation in fish liver and sediments. Some researchers indicated that elevated levels of heavy metals such as Zn and Cu in surface sediments come from mine

Table 4
Heavy metals concentrations in fish muscle of Nile Tilapia (*Oreochromis niloticus*) of Lake Nasser and comparison of HMs concentration values with standard levels stipulated by different regulations.

Elements Concentration (mg.kg^{-1})	Measuring sites						Standard levels(mg.kg^{-1})				
	1 Abu-Simble	2 Armina	3 Tushka	4 Korosko	5 Kalabsha	6 High Dam	[a] EC 2005	[b] FAO 2012	[c]FAO/WHO, 2011	[d] WHO 1989	[e] MAFF 2000
Cu	1.20	2.25	9.17	2.25	5.26	6.18	10	30	30	30	20
Zn	8.50	12.78	15.70	13.20	13.65	14.9	–	30	40	100	50
Cd	0.15	0.15	0.23	0.18	0.20	0.24	0.05	0.05	0.5	1	0.2
Pb	0.10	0.20	0.50	0.20	0.20	0.50	0.20	0.5	0.5	2	2
MPI	0.63	0.96	2.02	1.02	1.30	1.82					

[a] EC, 2005 (European Community, Commission Regulation No. 78/ 2005).
[b] FAO, 2012 (Food and Agriculture Organization, Animal Feed Resource Information System, 2012).
[c] FAO /WHO limit 2011 (The Joint FAO/WHO Expert Committee on Food Additives, WHO Technical Report Series 960).
[d] WHO, 1989 (Heavy Metals Environmental Aspects, 1989 Environment Health Criteria. No. 85).
[e] MAFF, 2000 (Ministry of Agriculture, Fisheries and Food, Aquatic Environment Monitoring of UK, Report No. 52, 2000).
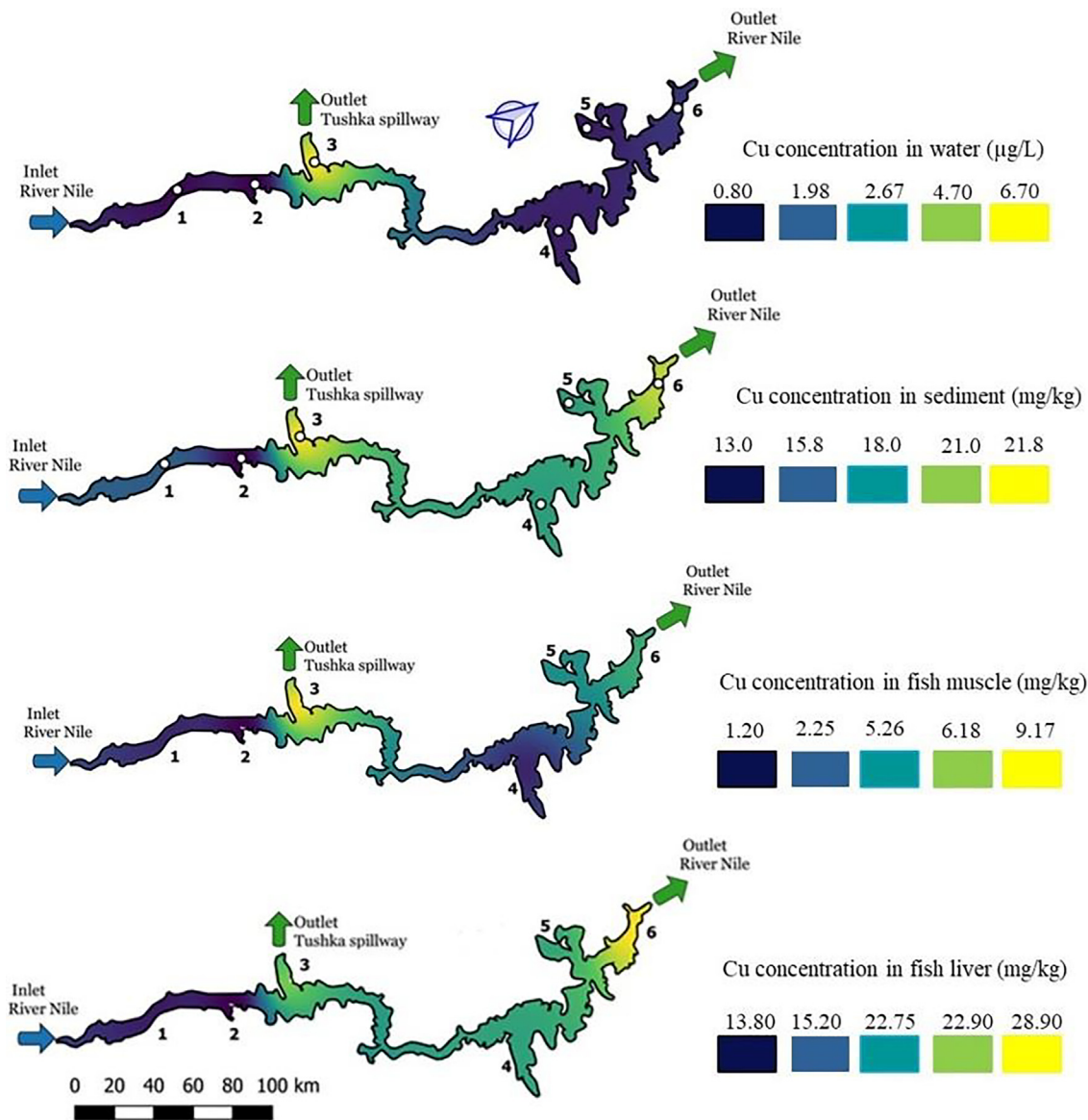
Fig. 2. Copper distributions along the lake in water, sediment, fish muscle and fish liver.

effluents, vehicular emission and commercial and industrial sources (Decena et al., 2018).

3.4.2. Zinc

As shows in Fig. 3, zinc concentrations in water, sediment, fish muscle and fish liver has been illustrated. Blue color highlights the lowest Zn concentration, which indicates the best water quality with respect to this heavy metal, whereas the yellow indicates high concentrations. The sequence of Zn concentrations in the samples were in the order of liver > sediment > muscle > water. The results show that water exhibited the lowest concentration (Table 1), whereas sediment and liver samples exhibited the highest values (19–45 and 37.5–58.10 mg.kg^{-1} respectively). The results show that zinc concentrations in the edible tissues of fish were within the normal variation according to the Canadian fish standard (51. 60 ± 2.80 mg.kg^{-1}) (Table S2).

3.4.3. Lead

The accumulation of lead in fish tissues can induce oxidative stress due to production of Reactive Oxygen Species (ROS), which induce potential synaptic damage and several malfunction implications in fish, as neurotoxicity. Moreover, exposure to lead has a negative effect on the immune responses in fish (Lee et al., 2019). Fig. 4 highlights the lead concentrations in water, sediment, fish muscle and fish liver; the blue color refers to the lowest concentrations, indicating the best water quality with respect to this heavy metal, whereas the yellow color indicates high values. The gradient of lead concentrations in samples is in the following order sediment > liver > muscle > water. The results show that water exhibited the lowest concentrations (Table 1), whereas the sediment and liver samples exhibited the higher concentrations in the lake (0.2–3 and 0.9–2.1 mg.kg^{-1} respectively).

3.4.4. Cadmium

Cadmium induces harmful effect on living cells, their membrane deterioration and destroys the DNA structure. Such severe damage result from the displacement of this heavy metals from its original binding sites (Igiri et al., 2018). Fig. 5 shows cadmium concentrations in water, sediment, fish muscle and fish liver. The blue color refers to its lowest concentrations, whereas the yellow
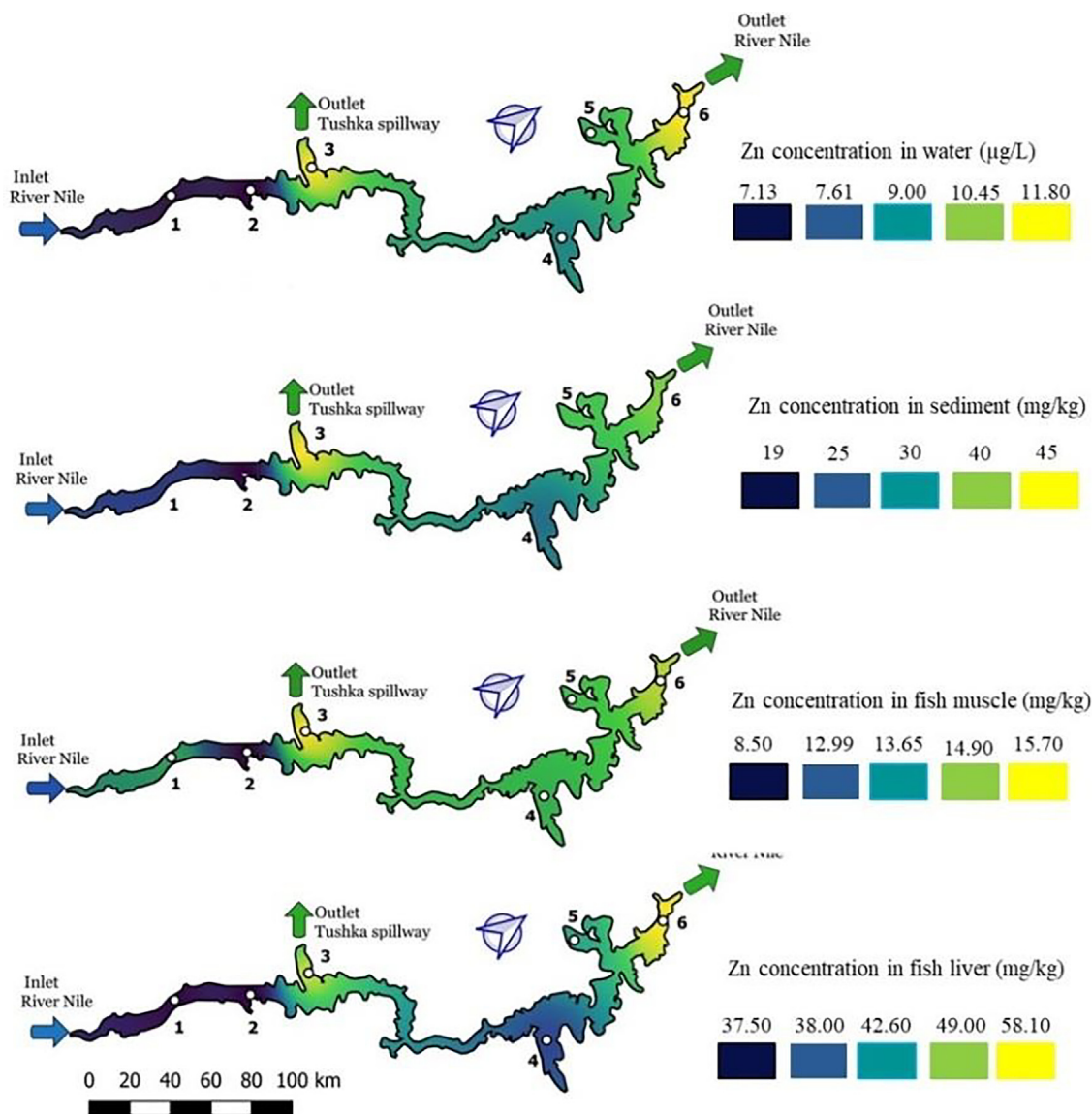
Fig. 3. Zinc distribution along the lake in water, sediment, fish muscle and fish liver.

indicates the highest values. The gradient of cadmium concentrations in samples is sediment > liver > muscle > water. The results showed that water exhibited the lowest concentrations (Table 1), whereas the sediment and liver samples exhibited the highest concentrations in the lake (0.3–0.5 and 0.18–0.356 mg.kg^{-1} respectively). Trace concentrations of this metal can negatively affect the metabolism and growth of fish by altering their DNA structure, causing dysfunction, disruption of cell membranes, inhibition of enzyme activities and oxidative phosphorylation. Equally, it induces direct toxic effects in humans, through food intake. Cadmium bioaccumulation was reported to induce nephrotoxicity and cause a specific renal failure as well as other associated health issues (Ismail and Rizk, 2016).

The evaluated MPIs ranged from 0.63 mg/kg to 6.40 mg/kg with the mean of 3.54 mg/kg. The highest MPI value has been reported in fish liver samples at sites 6 and 3 (6.40 and 6.23 respectively) and in sediment was at sites 3 and 6 (5.57 and 5.23 respectively), while the lower MPI value were in fish Muscles at site 1 (0.63 mg/kg) (Fig. S2). The findings of MPI in the present study were much lower than that of *Rutilus rutilus* in Pluszne Lake (Luczynska et al., 2018).

The northern part of the lake showed the higher contamination with heavy metals compared with the southern part, except site 3 which is highlighted by yellow in Fig. 6. The high recorded values for all measured heavy metals in this site are perhaps related to the ongoing agricultural activities in Tushka region, nearby Tushka spillway outlet. The overall water quality of Lake Nasser is below maximum permissible levels of international standards and specifications. Therefore, it can be concluded that the water of Lake Nasser is safe for human consumption, agricultural activities and animal husbandry. Maintaining the water quality of the lake within these acceptable values represents an important mission for the sustainable development in Egypt, therefore all necessary actions must be implemented for the protection of Lake Nasser. Fig. S1 shows the correlation between the contamination with heavy metals and the types (i.e., water, sediment, liver and muscles) of investigated items. The cluster tree shows a high positive correlation between zinc and lead concentrations in water and its accumulation in sediment and fish liver (0.9 and 0.81; 0.94 and 0.93, respectively). The correlation between copper concentrations in water and fish muscle (0.88) was higher than that of liver samples (0.73). The copper is directed towards cell tissues in
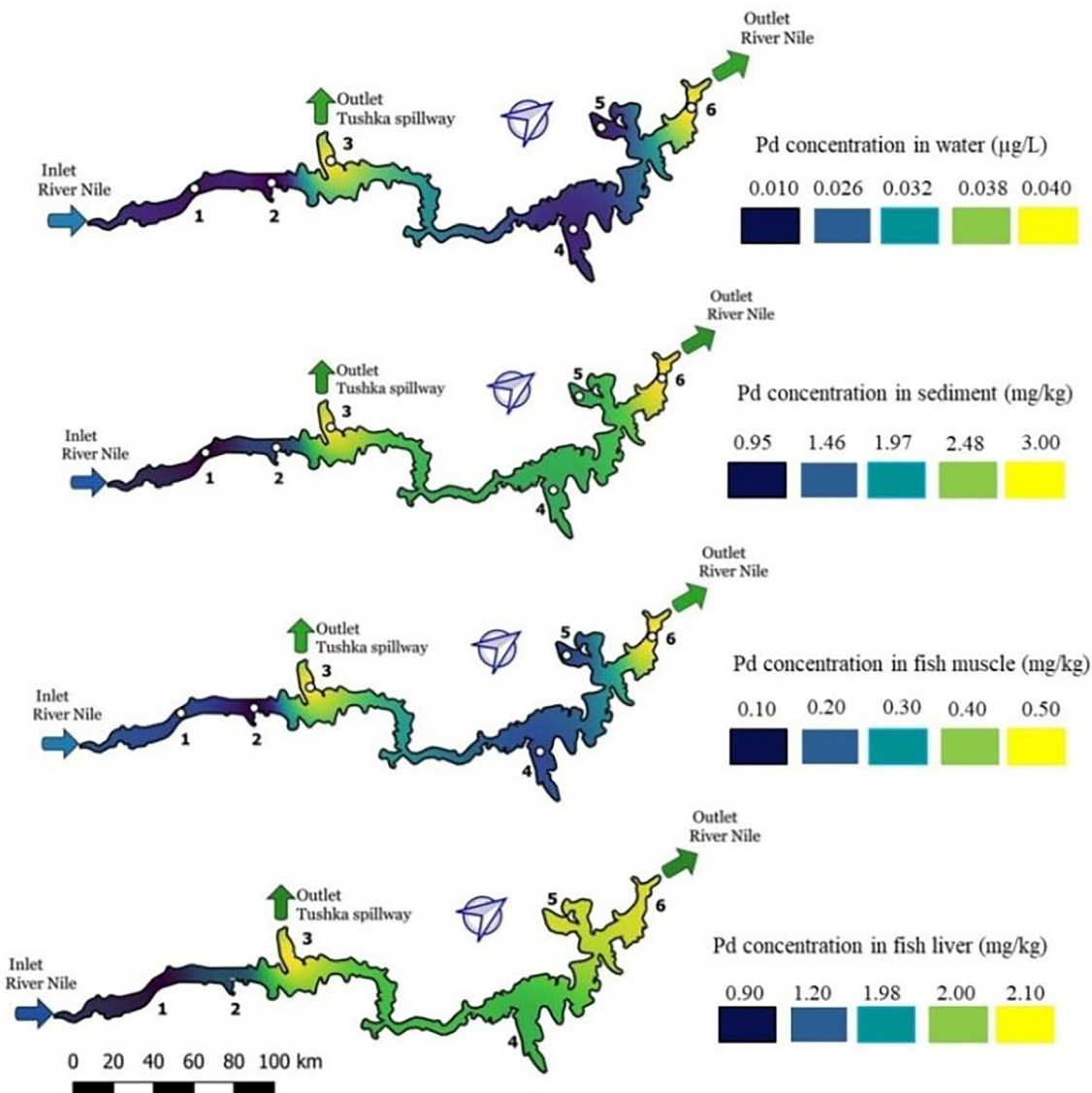
Fig. 4. Lead distribution along the lake in water, sediment, fish muscle and fish liver.

higher amounts than it does in liver, in order to participate in the protective role of the antioxidant enzymes. On the other hand, copper concentration in water exhibited a high positive correlation with sediment (0.91), given that the latter usually adsorbs the dissolved metals. In case of cadmium, the results showed a positive correlation between its concentration in water and in fish muscle, sediment and fish liver (0.91, 0.82 and 0.73 respectively). Fig. S1 confirms the increased risk for cadmium, because this element does not accumulate in the sediment in a large amount. However, it does accumulate in muscle in greater proportion. That is emphasize that Cadmium is not essential for fishes' metabolic processes, and is potentially dangerous at lower concentrations compared to the essential metalloids (Delahaut et al., 2020). Fish organs comprise an effective target for predicting the effects of water pollutants, as a result of the positive correlation between the bioaccumulation of heavy metals in fish tissues and their concentration in water. Therefore, the current study emphasized the importance of better understanding of heavy metals bioaccumulation in fish organs. Moreover, another aim of this survey was to provide a comprehensive image of the heavy metal status in this lake. One major advantage of the current study, as opposed to other previous attempts, was the high accuracy of heavy metal measurements by using certified reference materials (CRM) within certain ranges.

4. Conclusions

Lake Nasser serves as the national water reservoir in Egypt. Heavy metal analyses in water, sediment and edible parts of fish indicated that water quality is excellent and that the fish are safe for human consumption. The sediment fulfilled a major role by absorbing dissolved metals from the aqueous form. The concentration of heavy metals in fish muscles and livers meets the specifications stipulated by international limits. Therefore, continuous monitoring and management actions must be carried to support appropriate decision-making in assessing the health of Lake Nasser. The current study also strongly suggests that legal actions are needed to be implemented by authorities to overcome pollution in the adjacent areas of Lake Nasser by reducing future pollution levels. However, given that the current survey focused solely
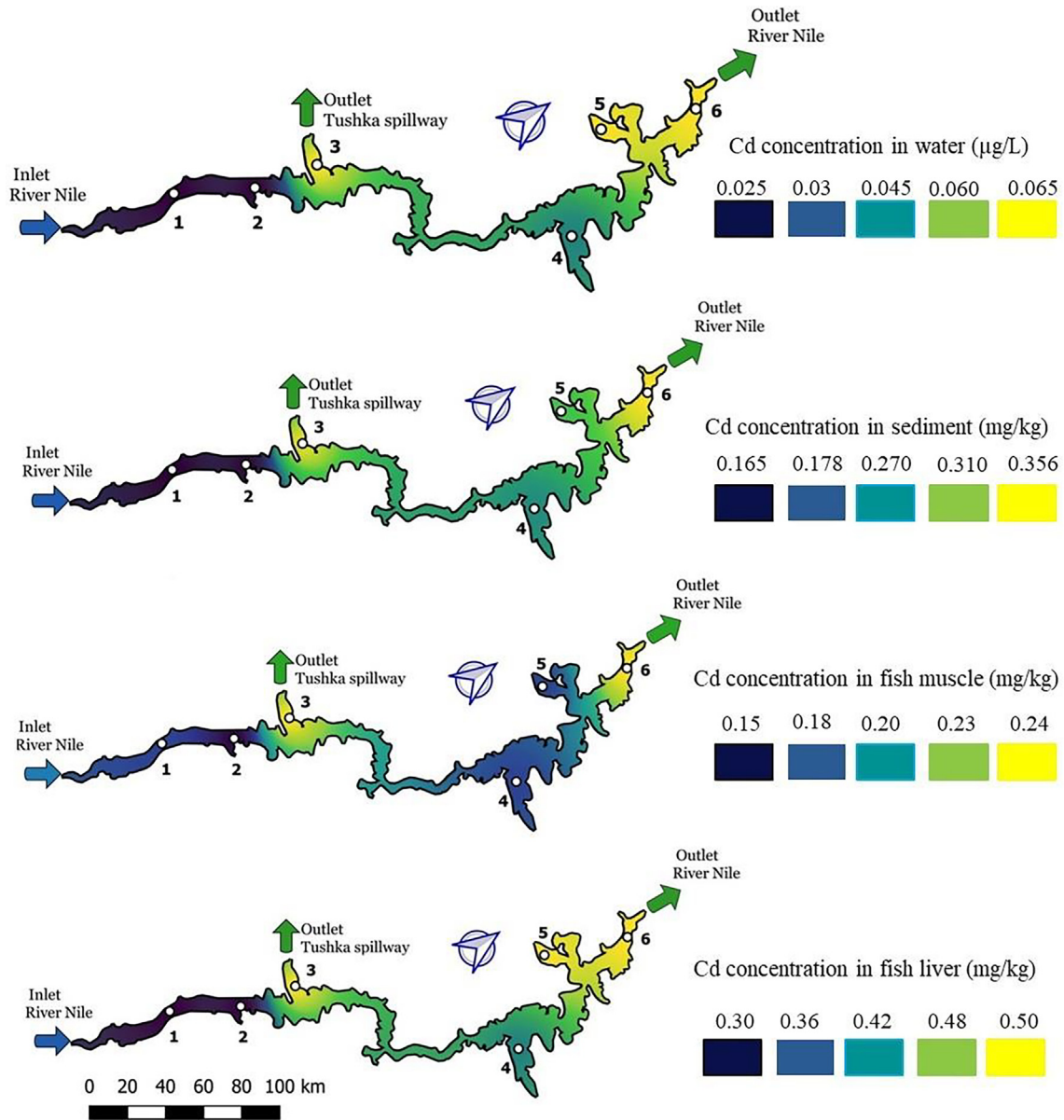
Fig. 5. Cadmium distribution along the lake in water, sediment, fish muscle and fish liver.
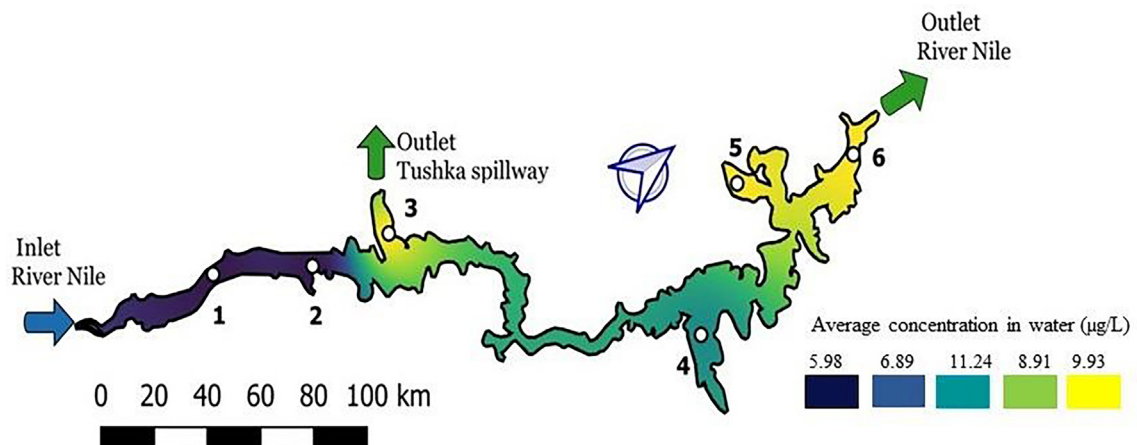

Fig. 6. General overview on Lake Nasser of mean concentrations of heavy metal distribution in water.

on a single fish species, future studies should widen their scope by including other aquatic organisms, such as other common fish species and macroinvertebrates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2021.101748.

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