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Impact of heavy metals on the food web in the Mediterranean lagoon, Lake Burullus, Egypt

by

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Abstract

Research on the impact of heavy metals and their accumulation in ecosystem elements of Lake Burullus is still scarce. Therefore, this study focuses on the relationship between the levels of heavy metals in the lake water, plankton communities and Nile tilapia (*Oreochromis niloticus*). The mean annual concentrations of Fe, Zn, Cu, Mn, Pb and Cd in water and fish samples were 527.8, 366.7, 162.6, 137.3, 119.8 and 3.6 μg l^{-1}, and 70.8, 43.6, 8.05, 1.2, 0.14 and 0.045 μg g^{-1} dry weight (d.w.), respectively. The study demonstrated the relationship between the accumulation of metals in fish muscles and their levels in the lake water ($p < 0.05$; $r = 0.7–0.9$), with the metal content in *O. niloticus* muscles being mostly below the permissible limits. The obtained results showed that the levels of the metals in the lake water are not correlated with phytoplankton and zooplankton, and their groups, except copper and zinc, are negatively correlated with phytoplankton ($r = -0.45$ and -0.58, respectively). The study concluded that the concentrations of the analyzed metals in Lake Burullus did not reach the effective levels that would have a significant impact on the distribution of phytoplankton and zooplankton, or a hazardous effect on *O. niloticus* and its safety for human consumption.

Key words: Lake Burullus, heavy metals, phytoplankton, zooplankton, *Oreochromis niloticus*

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Introduction

Metals enter the aquatic environment through atmospheric deposition, erosion of the geological matrix, or as a result of human activity through industrial, domestic, agricultural drainage, and mining waste (Jewett & Sathy Naidu 2000). Some of the metals at low concentrations are very important for life, because they play an important role in metabolic processes of all living organisms. However, high concentrations of these metal ions are toxic to most organisms (Bahnasawy et al. 2009). Metals are the most common pollutants in aquatic ecosystems. Their accumulation and distribution in water and sediments of water bodies affect aquatic organisms (Mohiuddin et al. 2011; Imam et al. 2020). Metals are good indicators when monitoring changes in the aquatic environment. However, information on their total concentrations in water and sediments is not sufficient to assess their ecological impact, because part of the total metal content is involved in biological processes of aquatic organisms (Abouel Fadl et al. 2016).

A food web in ecosystems is a complex pattern of feeding relationships between species at various levels, giving a complicated picture of ecosystem structure, species interactions and biodiversity (Dunne et al. 2004). It comprises many food chains that are interconnected at different trophic levels in an ecosystem (Post 2002). Heavy metals have a great impact on aquatic food webs, which can change the community structure by reducing species abundance and diversity in any water body. The ability of aquatic species to cope with high levels of metal contamination varies (Landers 2016). The impact and accumulation of heavy metals on/in aquatic organisms is an important issue for ecologists to understand the fate of trace elements in the food web dynamics (Muduli et al. 2012).

Phytoplankton are the primary producers in aquatic food webs, followed by zooplankton (primary consumers) that feed mostly on phytoplankton and then turn into energy for higher trophic levels (D'Alelio et al. 2016). Moreover, plankton is a major food source for tertiary producers, juveniles and some adult fish, leading to increased yield of fish production (Xie et al. 2008). Plankton organisms are very sensitive to environmental changes and respond to pollutants, including heavy metals (Lougheed & Chow-Fraser 2002; Chouteau et al. 2004, Anufriieva et al. 2020). Therefore, any changes in plankton structure can be followed by changes in the biodiversity and species structure of the whole food web.

Metals can be transferred through aquatic food webs to fish, which are often at higher levels of the food chain (Chen et al. 2000). They can be accumulated in fish tissues by direct consumption of water across permeable membranes of gills and the digestive tract (Ribeiro et al. 2005). Furthermore, fish can accumulate large amounts of these metals in their tissues (Mansour & Sidky 2002; Daviglus et al. 2002), which can be transferred to humans through fish ingestion (Imam et al. 2020). Some of the heavy metals do not perform essential functions in living organisms. Therefore, these metals are very toxic even at very low concentrations for all life forms, including human health (Järup 2003). Contamination by toxic metals in fish muscles can be transferred to humans, which leads to serious health problems in humans (Alinnor & Obiji 2010). Of all coastal water bodies, lagoons are characterized by high productivity and are ideal for aquaculture projects, however, they are very sensitive to environmental changes and human activity (Kennish & Paerl 2010).

A total of five coastal lakes (Manzala, Burullus, Edku, Mariut, and Bardawil) are directly connected to the Egyptian Mediterranean Sea, except Lake Mariut (El-Shabrawy & Bek 2018). Lake Burullus has a unique ecosystem, which is of great importance to foraging habitats, refuge, and breeding of migratory water birds (Goher 2009). In 1988, Lake Burullus was declared a Ramsar site according to the Ramsar Convention (dealing with wetlands of international importance as waterfowl habitats). It was also declared a protected area by Prime Minister's Decree No. 1444 of 1998 (El Sayed et al. 2019, Shaltout et al. 2017), because it is an important habitat for marine fish and their regeneration, and a resting area for migratory birds (Assar et al. 2015). Lake Burullus is the second largest natural lake in Egypt and the largest fish producer of fish of all Egyptian lakes (El Sayed et al. 2019). In 2016, it produced 67.577 t, in addition to about 670.000 t produced in related aquaculture processes. The production of the lake and its aquaculture ponds accounted for about 42.5% of the total fish production in Egypt (GFARD, 2018; El Sayed et al. 2019). However, the lake receives huge quantities of drainage water from many agricultural drains. As a result, the ecosystem of the lake is very vulnerable to degradation (Younes & Nafea 2012; Assar et al. 2015).

While many studies have been conducted to investigate the relationship between heavy metals and fish in Lake Burullus (Yosef & Gomaa 2011; El-Batrawy et al. 2018), the relationship between metals and other elements of the food web (e.g. plankton) in Lake Burullus has not yet been investigated (Nafea & Zyada 2015). Therefore, this study focuses on the relationship between heavy metals and some elements of the food web in Lake Burullus, including plankton communities and Nile tilapia (*Oreochromis niloticus*).

Materials and methods

Study area

Lake Burullus is a brackish shallow lake, located in the north of Egypt, which is connected to the Mediterranean Sea through a small outlet (EL-Boughaz, 250 m wide and 5 m deep). It lies between 30°30′E and 31°10′E longitude and 31°21′N and 31°35′N latitude (Fig. 1, Table 1). Lake Burullus is a shallow water body with a depth varying from 0.4 to 2 m (Goher 2009). It has an oblong shape with a length of about 47 km and a width of 4 to 14 km, on average about 11 km (El-Adawy et al. 2013; El Sayed et al. 2019).

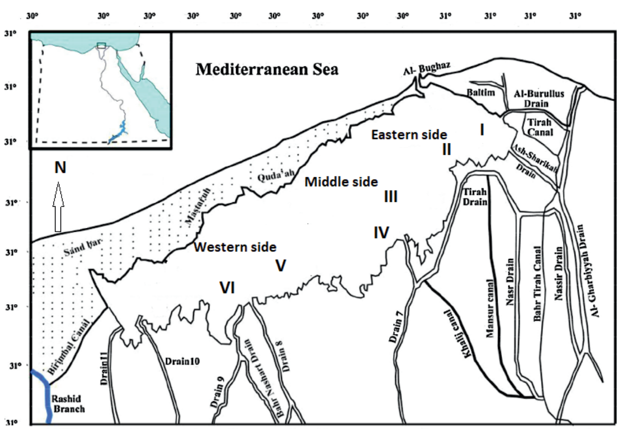

Figure 1

Map of Lake Burullus showing the sampling sites

Table 1

Longitude and latitude of the selected sites of Lake Burullus

Sector	Site	Longitude	Latitude
Eastern	I	31°3.853′E	31°33.199′N
	II	31°0.484′E	31°32.057′N
Middle	III	30°56.914′E	31°30.286′N
	IV	30°56.772′E	31°27.574′N
Western	V	30°45.836′E	31°25.832′N
	VI	30°44.351′E	31°24.604′N

The lake receives about 4 billion m^3 of agricultural drainage water per year from the Nile Delta area, which accounts for 97% of the lake water (El Sayed et al. 2019; Eid 2012); the remaining 3% is precipitation and groundwater (Oczkowski & Nixon 2010). The Burullus lagoon is affected mainly by agricultural drainage water mixed with different types of waste from fish farms, industrial and domestic wastewater effluent through numerous drains (Burullus east drain, El-Khashaa drain, Terra, drain 7, drain 8, drain 9, drain 10, drain 11, Zaghloul drain and Burullus west drain). For several years, the Brimbal canal carried freshwater from the Nile to the lake. At present, the canal receives only small amounts of water from the Nile, instead it receives various types of wastewater from minor drains (El Sayed et al. 2019).

Sampling program

Seasonal sampling was performed from November 2016 to July 2017. Lake Burullus was divided into three sectors – the eastern, middle and western sector close to the drainage sources – to cover the most polluted areas in the lake as shown in Figure 1. Surface water and plankton samples were collected from six sampling sites (two per sector), while fish samples (*O. niloticus*) were collected from three sites (one site per sector) as shown in Table 1.

Measurement of physicochemical parameters

Temperature, pH and electrical conductivity (EC) were measured in situ using a pH meter (Multi Set 430i WTW). Transparency of the water column was determined using a black and white enamel-coated Secchi disk with a diameter of 30 cm. Dissolved oxygen (DO) was fixed in situ, then measured in the laboratory according to APHA (2005).

Analysis of heavy metals in water and fish

Concentrations of Fe, Cu, Pb, Mn, Zn, and Cd in water samples were determined according to APHA (2005). A 500 ml sample of water was placed in a clean glass beaker and 10 ml of concentrated nitric acid was added. The sample was boiled on a hotplate until complete digestion. The remaining volume of the sample was supplemented to 100 ml by deionized distilled water. To determine the concentrations of heavy metals in the muscles of O. *niloticus*, fish samples were dried in a thermostatic oven at 105°C. One gram of dried samples was digested by adding 5 ml of each concentrated perchloric and nitric acids. The digestion was carried out on a hotplate (200 to 250°C) until clear solution was obtained. The solution was then filtered through an acid-resistant 0.45 mm filter paper and diluted to 25 ml by deionized water (Kotze et al. 2006).

The digested solutions of water and fish samples were used for the quantitative determination of heavy metals using an atomic absorption reader (SavantAA AAS with GF 5000 Graphite Furnace).

Histological studies

Samples of fish skin and muscles, representing Nile tilapia communities in the lake (different lengths and sexes), were fixed in 10% neutral buffered formalin solution, routinely embedded in paraffin, sectioned at 5 μm, then stained according to Harris' haematoxylin and eosin method (Bernet et al. 1999), microscopically examined and photographed using a microscopic camera.

Plankton analysis

For phytoplankton quantitative analysis, one liter of surface water sample was fixed with 2% Lugol's iodine. Samples were left to settle for 2 days and concentrated to 10 ml by siphoning the top layer of the sample with silicon tubing without disturbing the bottom layer. Samples were examined under a compound microscope (MOTIC BA 410, 100–400× magnification). Phytoplankton specimens were identified to the species level whenever possible. Phytoplankton numbers were expressed as a number of cells per liter.

To study zooplankton abundance and composition, 30 l of surface water was filtered through a 55 μm mesh zooplankton net. Samples were examined under the compound microscope (MOTIC BA 410, 100–400× magnification) and specimens were identified at the species level whenever possible. Zooplankton numbers were expressed as a number of individuals per cubic meter.

Statistical analysis

Principal Component Analysis (PCA) and Pearson's correlation matrix (r) were employed using the Xl stat 2016 software to determine the relationship between heavy metals in water and plankton. These analyses were also carried out to determine the effect of heavy metals in water on their accumulation in skin and muscles of *O. niloticus*.

Results

Physicochemical characteristics

Physicochemical parameters of the lake are shown in Table 2. Temperature varied in ordinary values (17.4–33.1) depending on the sampling time. EC values slightly fluctuated between seasons, however, they considerably varied between individual sites. The highest value (10.8 mS cm^{-1}) was recorded at site I, while the lowest (4.5 mS cm^{-1}) at site VI in the western sector. The highest value (70 cm) of transparency was recorded at site I in autumn, while the lowest value (28 cm) was recorded at site VI in summer. The pH values were in the alkaline range and slightly fluctuated between the sites and seasons. The DO values were high in winter – up to 9.3 mg l^{-1} at site I, while the lowest value (3.5 mg l^{-1}) was recorded at site VI in summer. These results are consistent with those obtained by El Sayed et al. (2019) and Eissa (2019).

Heavy metals in water

Mean annual concentrations of metals in water samples were in the following order: Fe > Zn > Cu > Mn > Pb > Cd. Seasonal fluctuations of metal concentrations were considerable, whereas their spatial variation was within a narrow range (Fig. 2). The highest values of metals were observed in winter, while the lowest values were recorded mostly in summer. Fe values fluctuated within a wide range (153 to 1098 μg l^{-1}). The highest value was recorded at site VI in winter, while the lowest value at site IV in spring. Mn values varied between 11 μg l^{-1} at site V in summer and 671 μg l^{-1} at site III in winter. Zn also showed large temporal fluctuations – the lowest value (11 μg l^{-1}) was recorded at sites II and V in summer, while the highest value (797 μg l^{-1}) was determined at site I in winter and autumn. On the other hand, Cu levels ranged from 15 μg l^{-1} at sites I and V in summer to 39 μg l^{-1} at site I in winter. The lowest value of Pb (7 μg l^{-1}) was recorded

Table 2

Ranges and mean values of physicochemical parameters in Lake Burullus

Parameter	Autumn	Winter	Spring	Summer
Temp. (°C)	21–21.6 (21.1)	17.4–18.9 (18.2)	25–26.6 (25.8)	31.4–33.1 (32.4)
Trans. (cm)	45–70 (59.2)	30–65 (39.7)	27–40 (33.1)	28–36 (29.8)
EC (mS cm^{-1})	4.5–10 (7.3)	5.3–10.8 (7.9)	4.5–9.9 (6.5)	4.8–8.5 (6.1)
pH	8.1–8.4 (8.2)	8–8.7 (8.5)	8.2–8.9 (8.4)	8.2–8.7 (8.4)
DO (mg l^{-1})	5.8–8.8 (7.01)	4.8–9.3 (7.7)	5.6–9.2 (7.4)	3.5–6.8 (5.6)

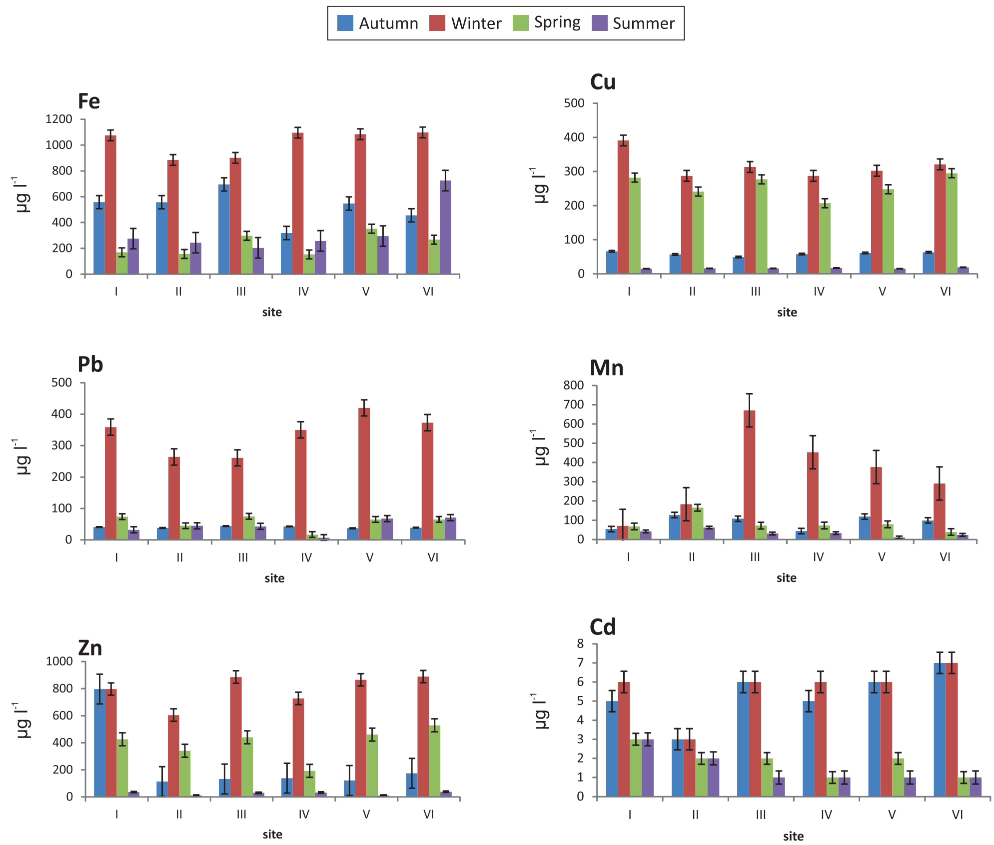

Figure 2

Seasonal variation in the concentrations of heavy metals in water at different sites of Lake Burullus

at site IV in summer, while the highest value (420 µg l^{-1}) was recorded at site V in winter. Cd values were significantly higher in winter and autumn at all sites compared to the values in summer and spring (Fig. 2).

Bioaccumulation of heavy metals in muscles of *O. niloticus*

Table 3 shows seasonal variations in the content of the studied metals in the muscles of *O. niloticus*, which follow the sequence: Fe >Zn > Mn > Cu > Pb > Cd. The Fe values ranged from 26.13 µg g^{-1} d.w. in the eastern sector in spring to 178.10 µg g^{-1} d.w. in the western sector in winter. The highest Zn value of 70.25 was recorded at the western site in winter, while the lowest – 30.025 µg g^{-1} d.w. – was recorded in the middle sector in summer. The content of Mn ranged from 3.850 to 16.55 µg g^{-1} d.w. at the middle and western sites in summer and winter, respectively. Cu concentration in muscles varied between 0.58 and 1.95 µg g^{-1} d.w. in the western sector in summer and winter, respectively. On the other hand, the highest Pb value of 0.28 µg g^{-1} d.w. was recorded in winter in the western sector and the lowest value of 0.05 µg g^{-1} d.w. in the middle sector of the lake in summer. The concentration of Cd ranged from 0.025 to 0.075 µg g^{-1} d.w. in the eastern and middle sectors in summer and winter, respectively. The obtained results indicate that the accumulation rate of the heavy metals in *O. niloticus* is related to the distribution pattern of heavy metals in water (Fig. 3), with a significant

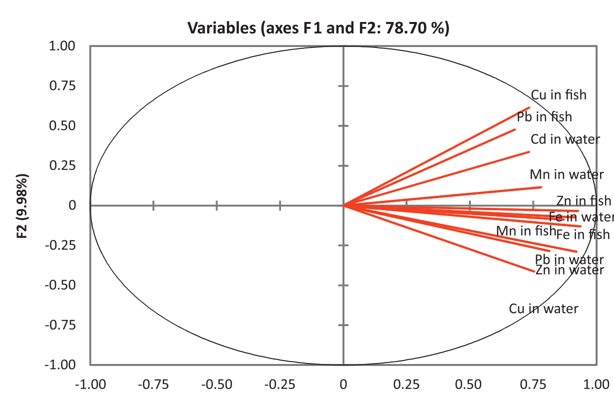

Figure 3

Principal Component Analysis (PCA) bi-plot of heavy metals in water and muscles of *O. niloticus* collected from Lake Burullus

Table 3

Seasonal variations in the concentrations of heavy metals (μg g^{-1} d.w.) in fish (*O. niloticus*) muscles collected from Lake Burullus

Metal	Site	Autumn	Winter	Spring	Summer	Means	permissible limits	References
Fe	East	129.37	79.72	26.13	67.64	35.35	……	……
	Middle	140.13	56.35	31.37	71.06	56.40		
	West	178.10	29.38	28.16	73.75	59.35		
Mn	East	5.75	15.65	4.00	3.85	7.31	……	……
	Middle	4.68	13.13	4.12	3.85	6.44		
	West	8.28	16.55	11.98	4.80	10.40		
Zn	East	37.50	56.95	41.35	38.75	43.64	40	Marks et al. 1980; Mohamed 2008
	Middle	39.95	51.83	33.38	30.03	38.79		
	West	38.55	70.25	51.60	33.08	48.37		
Cu	East	1.05	1.15	1.10	0.88	1.04	30	Marks et al. 1980; Mohamed 2008
	Middle	1.33	1.60	1.23	0.83	1.24		
	West	1.93	1.95	1.13	0.58	1.39		
Pb	East	0.12	0.13	0.13	0.10	0.12	2	Adeyeye 1993; Mohamed 2008
	Middle	0.13	0.14	0.13	0.05	0.11		
	West	0.20	0.28	0.23	0.11	0.20		
Cd	East	0.04	0.08	0.05	0.03	0.05	2	FAO 1992
	Middle	0.05	0.05	0.05	0.03	0.04		
	West	0.05	0.03	0.05	0.05	0.04		

positive correlation ($p < 0.05$; $r = 0.7$ to 0.9). In addition, the concentrations of metals in the muscles of *O. niloticus* were considerably higher in winter and lower in summer, with small spatial fluctuations and a slight increase in the western sector of the lake.

Impact of heavy metals on histopathology of *O. niloticus* muscles

Figure 4 shows that *O. niloticus* muscles collected from all sites were affected by a number of pathological changes, varying from season to season. In winter, severe pathological alterations were found in the skin and muscles, including edema and parasite. In autumn, the separation in epidermis and hemosiderin was observed. The dermis layer showed degeneration and hemosiderin formation in spring. In summer, histological changes were less severe compared to the other seasons and included degeneration and edema in the muscle layer.

Plankton

Phytoplankton

Phytoplankton was represented by 89 taxa that belong to the following classes (listed according to their abundance): Bacillariophyceae (42%), Chlorophyceae (23%), Cyanophyceae (17%), Euglinophyceae (16%), Dinophceae (0.9%), Conjugatophyceae (0.8%), Synurophyceae (0.2%) and Chrysophyceae (0.1%). Data showed significant spatial and seasonal differences in the distribution of phytoplankton. Phytoplankton was more abundant in summer, while in spring its abundance declined sharply to the lowest level (Fig. 5). As for the spatial distribution, phytoplankton densities were relatively high at the western sites of the lake. The highest total phytoplankton density was recorded at site V in summer – 189.9 × 10^7 cells l^{-1} and it significantly decreased to 54 × 10^5 cells l^{-1} at site I in spring (Fig. 5). Dominant groups of phytoplankton followed a similar seasonal distribution pattern as total phytoplankton with minor differences in the spatial distribution pattern (Fig. 5). Bacillariophyceae reached the highest density (81 × 10^7 cells l^{-1}) at site V in summer, while it decreased to the lowest density (5 × 10^5 cells l^{-1}) at site VI in spring. *Cyclotella meneghiniana* and *Lindavia ocellata* were the most dominant species of Bacillariophyceae during the study period. They accounted for 32.6 and 25.7% of all Bacillariophyceae, respectively. The two species reached the maximum abundance in summer with average density of 11 × 10^6 and 8702 × 10^4 cell l^{-1} and declined in spring to the lowest average density of 17 and 4 × 10^4 cell l^{-1}. Chlorophyceae and Cyanophyceae reached their maximum densities (50.4 and 39.6 × 10^7 cells l^{-1}, respectively) at site V in summer, while

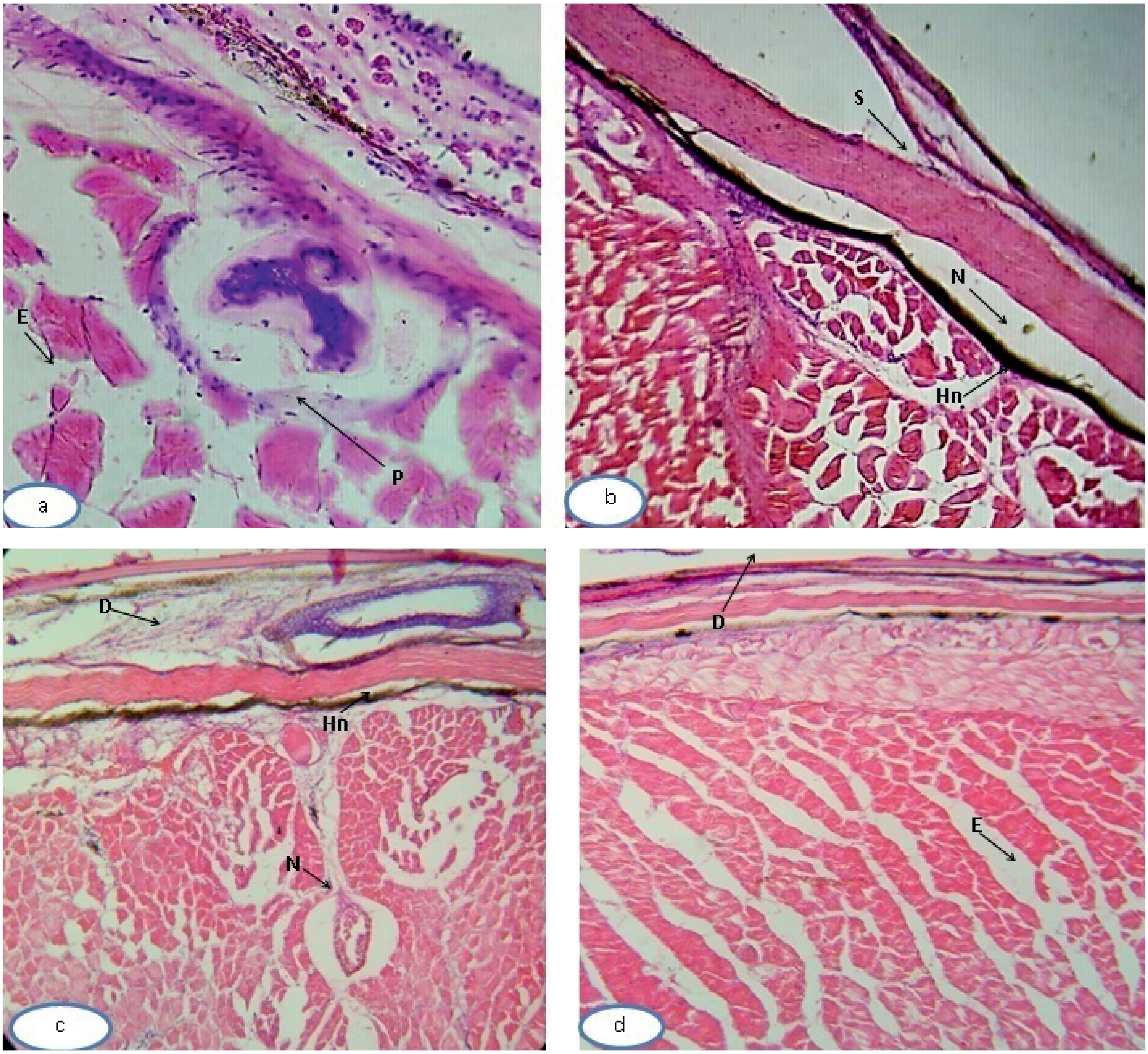

Figure 4

Vertical section in muscles of *O. niloticus* collected from Lake Burullus (at 400× magnification and using haematoxylin and eosin dyes) showing: a – edema (E), parasite (P), hemolysis (Hs) in winter; b – separation (S) in epidermis, necrosis (N), hemosiderin (Hn) in autumn; c – degeneration (D) in dermis, necrosis (N), hemosiderin (Hn) in spring; d – egeneration (D) and edema (E) in muscle layers in summer.

they declined to the lowest densities (10 and 15 x 10^5 cells l^{-1} at sites II and I, respectively) in spring. Among the Chlorophyceae species, *Ankistrodesmus falcatus*, *Scenedesmus armatus* and *Ankistrodesmus fractus* were the most dominant in the study area. While, *Phormidium inundatum*, *Chroococcus minor*, *Anabaenopsis circularis* and *Gloeocapsa punctata* were the dominant species of the Cyanophyceae group. Summer was the most productive season for these species.

The relationship between heavy metals and phytoplankton was determined using the principal component analysis (PCA) as shown in Figure 6. The results show no significant correlation between total phytoplankton and heavy metals, except for Cu and Zn, for which the correlation was negative ($r = -0.45$ to -0.58, $p < 0.05$).

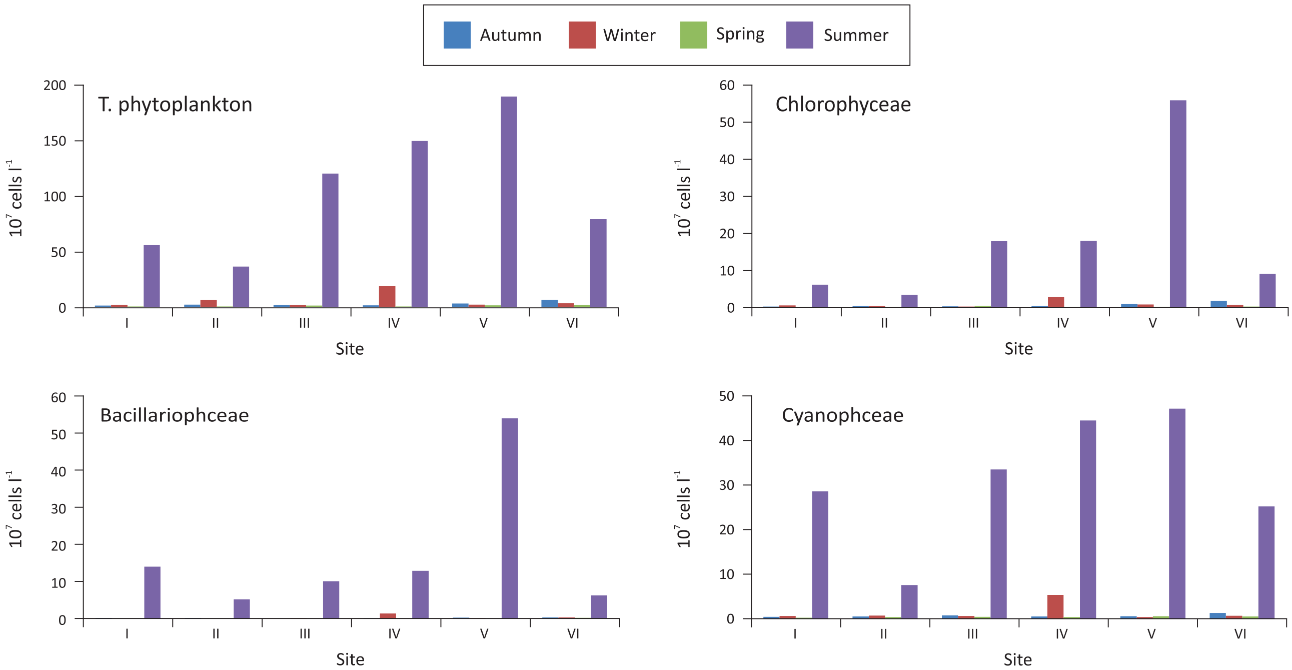

Figure 5

Seasonal distribution of total phytoplankton and its dominant groups (cells l^{-1}) at different sites of Lake Burullus

Zooplankton

Zooplankton in Lake El-Burullus was represented by 31 taxa (20 Rotifera, four Copepoda, four Cladocera and three Protozoa). Rotifera was the main dominant group in this study, representing about 75.6% of all zooplankton species, followed by Copepoda (17.4%), Cladocera (6.4%) and Protozoa (0.7%). The highest total zooplankton densities were observed at sites V and II in summer (1 089 650 and 1 026 300 ind. m^{-3}, respectively; Fig. 8). The distribution of Rotifera followed a similar pattern, with the highest density (1 023 650 ind. m^{-3}) at site V in summer. Rotifers were dominated by *Brachionus plictilis*, *Brachionus angularis* and *Brachionus calyciflours*, which were more abundant in summer. Copepods reached the highest density of 14 8500 ind. m^{-3} at site V in spring and 141 900 ind. m^{-3} at site IV in winter. On the other hand, considerably high density of Copepoda was observed in summer at sites II and III (Fig. 7). Nauplius larvae contributed about 56.17% to the total Copepoda, while *Acanthocyclops trajani* occurred during the study period as dominant adult copepods (13.3%). Similarly to the distribution pattern of total Copepoda, Cladocera were abundant in summer at sites I and II with densities of 198 000 and 393 000 ind. m^{-3}, respectively (Fig. 7). *Diaphanosoma excisum* was the most dominant species of Cladcera in this study. It contributed about 62.44% to the total Cladocera density and its distribution followed a similar pattern as total Cladocera.

The PCA analysis showed that zooplankton and its groups in Lake Burullus were not affected by the determined levels of heavy metals (Fig. 8). Total zooplankton and its groups insignificantly correlated with all heavy metals.

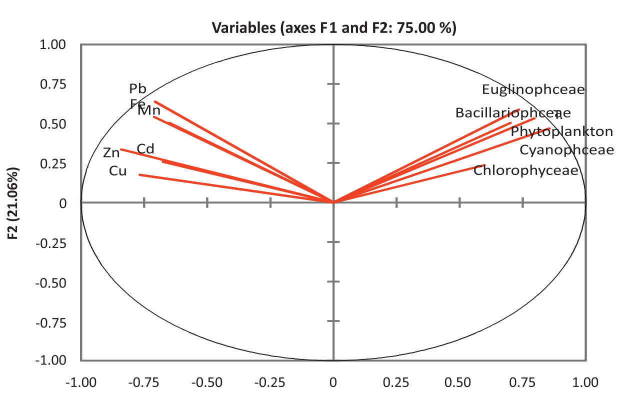

Figure 6

Principal Component Analysis (PCA) bi-plot of heavy metals and phytoplankton of Lake Burullus

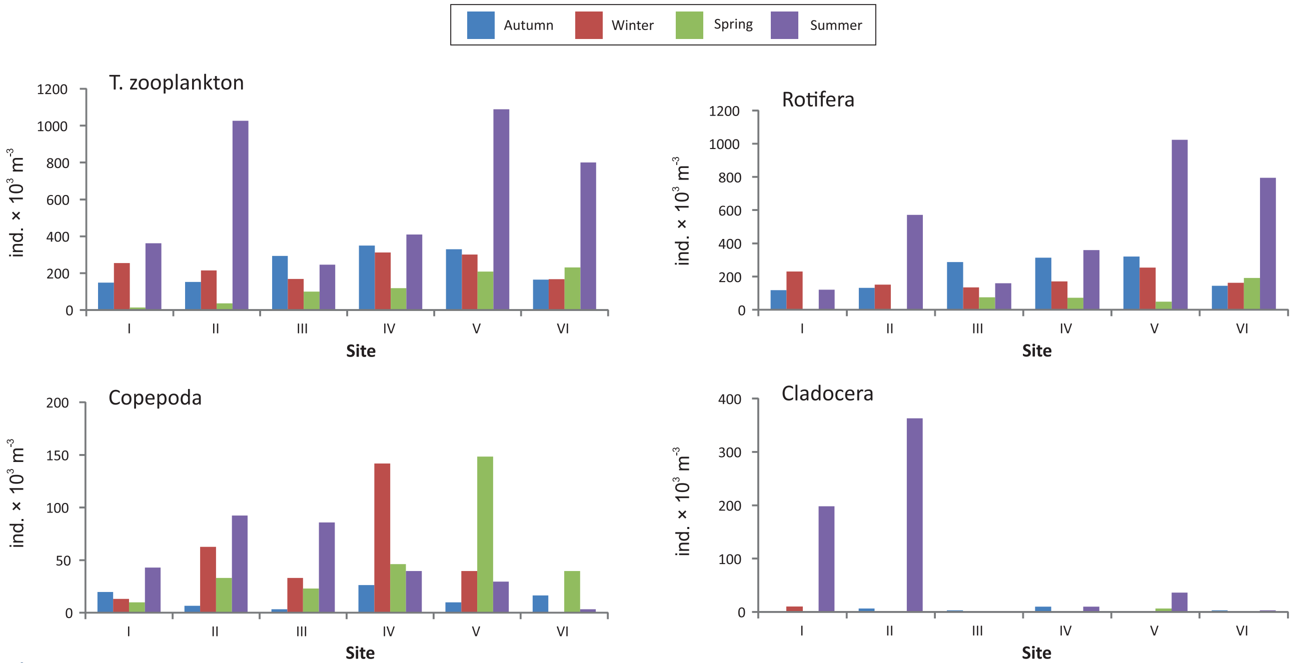

Figure 7

Seasonal distribution of total zooplankton and its dominant groups at different sites of Lake Burullus

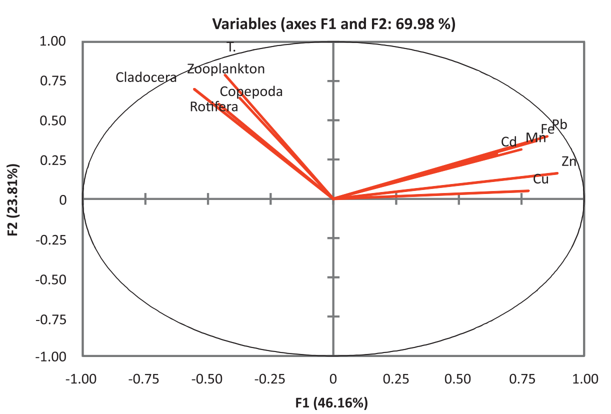

Figure 8

Principal Component Analysis (PCA) bi-plot of heavy metals and zooplankton of Lake Burullus

Discussion

Seasonal and spatial changes in water temperature are determined by climate change and are related to sampling time. During the study period, the temperature of water in Lake Burullus was suitable for fish and, in general, was within the permissible limits (8–28°C) for the aquatic life, except in summer. These findings are consistent with the results obtained by El Sayed et al. (2019). The water in the lake is characterized by turbidity throughout the year due to huge amounts of waste that are introduced into the lake through a number of drains. However, a slight increase in transparency during the cold season, especially at the eastern sites, is attributed to the intrusion of seawater during the drought period. Whereas the decreasing transparency values at the western sites, especially in summer, may be attributed to the increased amount of the drainage water that enters into the lake (Negm et al. 2018). The increase in EC values in winter and autumn compared to summer and spring may be related to the lack of freshwater supply during the drought period and periodic intrusion of seawater through the El-Boughaz outlets (EL-Zeiny & EL-Kafrawy 2016; El Sayed et al. 2019). The increase in DO concentrations in autumn and winter may be due to the water movement by wind action and the decrease in water temperature and increasing oxygen solubility (Radwan 2005; Goher et al. 2015; El Sayed et al. 2020). The lowest value of DO at the western sites in summer may be due to waste discharges that are characterized by high content of inorganic and organic matter. Moreover, the presence of nutrients can lead to a decrease in DO concentrations as a result of increased microbial activity during the degradation of organic matter (Sharaky et al. 2017; El Sayed et al. 2020). This can be attributed to the fact that the oxygen stability is low in summer and its utilization rate increased through biochemical reactions at high temperatures (Younis & Nafea 2012).

Heavy metals are among the major pollutants discharged into the aquatic environment due to their toxicity, accumulation and biomagnification by aquatic organisms (Goher et al. 2019). In the present study, the concentrations of heavy metals in Lake Burullus were higher in winter compared to other seasons, which is consistent with the results obtained by El-Batrawy et al. (2018) and Younes & Nafea (2012). On the contrary, Eissa (2019) reported that high levels of heavy metals were recorded in the hot seasons (summer and spring), while the lowest values were recorded in the cold seasons (winter and autumn).

The study revealed that Fe levels were slightly increased at the western sites, particularly during the cold season, which can be attributed to the impact of agriculture waste and inorganic fertilizers introduced into the lake through drains 8 and 9. The sediments in this area are dominated by clay that plays an important role in the distribution of iron (Masoud et al. 2011; Krupinska 2017). The large amount of Mn in winter can also be attributed to the agricultural and domestic sewage drainage, or may result from the decomposition of organic matter and dead microorganisms accompanied by the release of metals into water (El-Sayed 2011; Ahmed 2012).

The differences in the zinc concentration were small between the sites, which may be correlated with the amount of drainage input and the content of organic matter (El-Amier et al. 2017). Nevertheless, the highest values of zinc during the cold seasons are attributed to the declining and decaying phytoplankton, in addition to the domestic effluents from the drains to the lake (El-Baz 2015; Goher et al. 2017). Also Ahmed (2012) attributed the highest value of Zn to the low water level during the drought period. The lowest values recorded during the hot season are attributed to the uptake of zinc by macrophytes, phytoplankton and zooplankton, as well as the process of intensive precipitation of zinc salts from the water column to the sediment due to high temperature (Melegy et al. 2019). No significant differences were found in copper concentrations between the study sites, however, the concentration of Cu was slightly higher at site I. This is may be due to the effects of effluent waste from the El Burullus and El-Khashaa drains. On the other hand, the highest concentration of copper in winter may be due to the agricultural drainage (El-Amier et al. 2017). The low concentration of Cu in summer may be due to the uptake of Cu by phytoplankton, which in this season occurs in high density (Beheary et al. 2014). Cu plays a biological role in normal metabolism and the growth of phytoplankton (Bahnasawy et al. 2011).

The maximum values of Pb in winter may be due to the pollution by industrial effluents and municipal sewage concentration (Chen et al. 2010; Nafea & Zyada 2015). Whereas the minimum value recorded during the hot seasons may be due to the uptake of Pb by phytoplankton, zooplankton, fish and other aquatic organisms (Goher 2002). On the other hand, the high concentration of Cd at site VI in winter and autumn may be attributed to the agricultural runoff from drains 8 and 9, where fertilizers, pesticides and other agrochemicals, in addition to the possible release of sediment-bound metals, are the main sources of Cd in inland water bodies (Beheary et al. 2014).

In general, the seasonal and spatial variation in metal concentrations may be related to the type and composition of chemical fertilizers and pesticides used in agricultural fields in the Nile Delta region, which reach the lake. The current study revealed that the levels of heavy metals in Lake Burullus were mostly relatively low and the lake is less polluted compared to other delta lakes, which is consistent with the results obtained by Chen et al. (2010) and Ghabour et al. (2013).

A significant positive correlation between the metals in the lake water and the muscles of *O. niloticus* was found ($p < 0.05$; $r = 0.7–0.9$). This correlation can be accounted for by the fact that fish are more affected by heavy metals due to their ability to accumulate metals (Adeyeye 1996). Heavy metals in the body of fish come mainly from their diet (EFSA 2005) or directly from water during the breathing process.

Western Australian Food and Drink Regulations recommended a level of 40 μg g^{-1} d.w. for Zn for human consumption (Marks et al. 1980; Mohamed 2008). Accordingly, the concentration of Zn in the muscles of the examined fish is still below the permissible level in spring, summer and autumn, while in winter its concentration is above the limit at all the study sites. The concentration of Cu in the muscles of the examined fish is still below the permissible level (30 μg g^{-1} d.w.) recommended by the National Health and Medical Research Council (Marks et al. 1980; Mohamed 2008). The present study revealed that the Pb concentration in the muscles of fish *O. niloticus* is still below the US FDA maximum permissible level for Pb (2.0 μg g^{-1} d.w.; Adeyeye 1993; Mohamed 2008). The concentration of Cd in the muscles of the examined fish is still below the permissible level for Cd (2.0 μg g^{-1} d.w.) recommended by FAO (1992).

Furthermore, the pathological alterations of *O. niloticus* tissues were severe in winter, which could be a direct result of the increasing content of heavy metals during this season (Sabae & Rabeh 2000). On the other hand, histopathological alterations in the tissues were less severe in the summer season, which

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may be due to the decreasing content of heavy metals. Histopathological alterations in fish skin and muscles are related to many factors, including heavy metals and changes in water quality (Yacoub et al. 2008; Abou El-Gheit et al. 2012). The histopathological alterations found in the muscles of the examined fish are consistent with those observed by many researchers who have studied the effects of different pollutants on fish muscles (Ramesh & Nagarajan 2013).

Plankton has been used as a bioindicator to monitor aquatic ecosystems and the integrity of water (Li et al. 2010). Phytoplankton is an important ecological tool to monitor aquatic ecosystems, and changes in the structure of their communities may indicate the beginning of environmental alteration (Tilman et al. 1982). Changes in the abundance, diversity and composition of zooplankton can also provide important indications of an environmental change (Escribano & Hidalgo 2000; Kimmel et al. 2006, Anufriieva et al. 2020). In the current study, phytoplankton was represented by 89 taxa belonging to eight classes. Bacillariophyceae, Chlorophyceae and Cyanophyceae were the largest classes. Phytoplankton was more abundant in summer and declined sharply to the lowest densities in spring. The comparison with previous studies showed more or less similar phytoplankton composition with the two dominant classes (Bacillariophyceae and Chlorophyceae) but different relative abundance values (Radwan 2005; Okbah & Hussein 2006; Nassar & Gharib 2014). Radwan (2005) attributed the maximum abundance values of phytoplankton in Lake Burullus in summer to high values of phosphate and nitrate, which leads to the development of phytoplankton. The insignificant negative correlation between the phytoplankton and metals, except for Zn and Cu, may indicate that the concentrations of these metals in Lake Burullus did not reach the effective levels that would have a significant impact on the distribution of phytoplankton in the lake. It is worth mentioning that microalgae have the ability to absorb and accumulate heavy metals from the environment through micronutrient transporters (Arunakumara & Zhang 2008; De Philippis et al. 2011). Moreover, they may be resistant to toxic pollution by binding heavy metals to specific intracellular compounds and/or by transferring these metals to a specific cellular chamber (Perales-Vela et al. 2006; Arunakumara & Zhang 2008). The significant negative correlation between Zn and Cu and phytoplankton can be attributed to their biological role in normal metabolism and the growth of phytoplankton, which results in their active uptake and storage (Bahnasawy et al. 2011). Sunda & Huntsman (1992) reported that the oceanic phytoplankton species reached their maximum growth rate at the lowest Zn concentrations. Further, Zn has a significant impact on the spatial distribution of phytoplankton species (Brand et al. 1983). According to Bilgrami & Kumar (1997), low concentrations of Cu and Zn are not toxic to green microalgae (*Closterium acerosum*, *Pediastrum simplex*, *Chlorella vulgaris* and *Scenedesmus quadricauda*), however, their growth is inhibited at slightly increased concentrations of these metals.

In the course of this study, zooplankton was represented by 31 taxa, belonging to Rotifera, Copepoda, Cladocera and Protozoa, where Rotifera was the main dominant group, which is consistent with the results reported by Dumont & El Shabrawy (2007) for Lake Burullus and Anufriieva et al. (2020) for Lake Magic. The total zooplankton and individual zooplankton groups were insignificantly correlated with all heavy metals contained in water of Lake Burullus. These results provide evidence of the dominance of Rotifera, followed by Copepoda and Cladocera in Lake Burullus. Gagneten & Paggi (2009) reported that Rotifera was the most tolerant group of zooplankton to heavy metal contamination in the lower basin of the Salado River (Argentina), followed by Copepoda and Cladocera. In the laboratory experiments cladocerans were also more affected by heavy metals than copepods (Roch et al. 1985). The insignificant correlation between zooplankton and metals may indicate that the concentrations of these metals in Lake Burullus did not reach the effective levels that would have a significant impact on the composition and abundance of zooplankton in the lake. Based on the collected data, the concentrations of these metals in Lake Burullus are too low to have a significant impact on the composition and abundance of zooplankton. Verma & Naranyan (2013) reported that the population of Ceriodaphnids declined at high concentrations of heavy metals. On the other hand, the toxicity of heavy metals to zooplankton is affected by some factors such as temperature and algal food density (Perez & Sarma 2008). Thus, higher temperatures and heavy metal concentrations lead to a decline of zooplankton populations (Buikema et al. 1974). High concentrations of metals during this study were recorded mostly in winter (low temperature), therefore their impact was not significant on zooplankton populations in the lake.

Conclusions

This study was conducted to monitor the impact of metals on the food web in Lake Burullus due to its location as well as its ecological and economic importance. As a result of the study, it was concluded that the concentrations of heavy metals in water of the lake and in the muscles of *O. niloticus* were correlated. The study shows no significant correlation between the lake plankton and metals, except for Zn and Cu, which are negatively correlated with phytoplankton. The obtained results may indicate that the concentrations of these metals in Lake Burullus did not reach the effective levels that would have a significant impact on the distribution of phytoplankton and zooplankton and the health of fish in the lake.

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