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Assessment of the status of selected heavy metals in water, sediments and a fish species (*Oreochromis niloticus*) of commercial value in Lake Nakuru with a focus on human health risks

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Abstract

The present study presents selected water quality parameters and the levels of heavy metals in water, sediments and Nile tilapia (*Oreochromis niloticus*) of Lake Nakuru. Nine sediments and nine water samples, as well as 30 specimens of Nile tilapia, were collected from the northern part of the lake. Physical parameters were measured in situ using multiple probes and metres. Heavy metals were analysed using an atomic absorption spectrophotometer (AAS). The pH, dissolved oxygen concentration, temperature, salinity and electrical conductivity ranged from 9.52 to 9.72, 4.58 to 8.62 mg/L, 23.40°C to 25.7°C, 2.39‰ to 2.81‰ and 4470–5226 µs/cm, respectively. Heavy metal levels (mean ± SD) were generally low in the water samples. Chromium values ranged between 7.16 and 9.19 mg/kg dw in sediment samples, and between 3.7 and 13.06 mg/kg dw in fish samples. Lead values ranged between 12.5 and 31.04 mg/kg dw in sediment samples and 4.06 and 9.95 mg/kg dw in fish samples. Arsenic values ranged between 9.5 and 21.7 mg/kg dw in sediments and below detectable limit to 2.11 mg/kg dw in fish samples. Mercury values ranged between .14 and .31 mg/kg dw in sediment samples and .12 and .35 mg/kg dw in fish samples. Cadmium was the only heavy metal concentration that was below the detection limit in the three matrices. Significant differences were observed for some heavy metal concentrations in water, sediments and fish across sites ($p < .05$). The levels of lead and chromium in fish were above the East African Standard, World Health Organization and European Union limits. The results of the present study recommend a possible reclassification of the lake, an immediate ban on fish harvesting and consumption from Lake Nakuru and a policy intervention on the fishery and pollution management.

KEYWORDS
health risk assessment, heavy metal pollution, Lake Nakuru, limnological changes, *Oreochromis niloticus*

1 | INTRODUCTION

Environmental pollution, largely due to anthropogenic activities, is on the rise globally (Hazrat et al., 2019; Murtala et al., 2012; Pandey & Singh, 2019; PEGC, 2016). Aquatic ecosystems are the destination of many contaminants and in many cases pollutants produced at different scales get into the aquatic environment at one point in time (Rai et al., 2019). Microbial contaminants, organochlorine pesticides, heavy metals and nutrients (nitrogen and phosphorus) are some of the pollutants mostly reported in aquatic environments (Kundu et al., 2014). Pollutants in aquatic environments tend to compromise the quality of ecosystem services particularly the provisioning services from these ecosystems.

Lake Nakuru was declared a conservation area in 1957, a bird sanctuary to protect the lesser flamingos in 1960 and Kenya's first Ramsar site in 1990 (Odada et al., 2004). However, the lake has continued to face a lot of impacts from catchment activities. The increase in human population and activities in its catchment has led to increased contamination of the lake. The use of fertilizers and pesticides in the Nakuru catchment to increase yields is of utmost importance given its being a high potential agricultural area (Junjiro & Masahisa, 2005). It is reported that Lake Nakuru catchment is among the drainage basin greatly affected by human activities compared to other saline lakes in the Kenyan Rift Valley system (Ndetei & Muhandiki, 2005).

Over the past few years, the water levels in Rift Valley lakes in Kenya have risen significantly leading to unusual hydrologic and limnological changes and Lake Nakuru was not an exception. There also has been an introduction of three freshwater species namely: Nile tilapia (*Oreochromis niloticus*), Blue spotted tilapia (*Oreochromis leucostictus*) and Victoria tilapia (*Oreochromis variabilis*) though the sources are unknown. Prior to these introductions, one saline fish species, the Lake Magadi tilapia (*Alcolapia grahami*) was found in the lake. Although some work covering several aspects on abiotic and biotic parameters in the lake was done, this study was a quick and informal cover of the lake status.

The introductions of the three fish species in Lake Nakuru has led to an emerging fishery. However, there is limited knowledge regarding the safety of these fish for human consumption. Furthermore, this study was necessary because even though Lake Nakuru is a protected area with no formal fishery, the inundation of the depressions outside the park create opportunities for fish exploitation. The aim of this study was to determine the levels of selected water quality parameters and heavy metals (arsenic, cadmium, chromium, lead and mercury) in water, sediments and Nile tilapia (*Oreochromis niloticus*) of Lake Nakuru and assess the health risk posed by consuming fish from the lake. The present study focused on the most abundant species in the lake's fishery; the Nile tilapia. Nile tilapia (*Oreochromis niloticus*) is a cichlid fish native to parts of Africa and the middle East and has been introduced to many other regions due to its popularity as a food fish. It has a deep-bodied, compressed shape. The species is bronze to brownish grey dorsally and laterally and white ventrically. It is one of the most farmed fish globally. Nile tilapia was first cultured in Kenya in 1924 and is the most cultured fish species (Munguti et al., 2022; Tibihika et al., 2022).

2 | MATERIALS AND METHODS

2.1 | Study site

Lake Nakuru is a shallow endorheic lake located in the Eastern arm of the Rift Valley. It has a regular shape, gentle slopes as well as a flat bottom (Leichtfried & Shivoga, 1995). It is situated in Nakuru County, south of Nakuru town roughly 157 km from Kenya's capital, Nairobi (Iradukunda et al., 2020). The lake has a surface area of 70 km^2 with a total catchment area of 1800 km^2 (Figure 1). Lake Nakuru lies at an altitude of 1759 m above sea level and is located at 0°23′ S and 36°7′ E within Lake Nakuru National Park (Iradukunda et al., 2020). Prior to the recent limnological changes, Lake Nakuru was famous for providing habitat to one of the largest population of lesser flamingos in Kenya (Odada et al., 2004).

2.2 | Location of sampling sites

All samples were collected from five sampling points: River Njoro mouth (00°19′21.1″ S and 36°04′39.9″ E) with an average depth of 3 m, Sewage discharge point (00°18′29.6″ S and 36°05′39.4″ E) with an average depth of 2.8 m, Nyati (00°20′06″ S and 36°06′50.8″ E) with an average depth of 1.9 m, Fishers' point (00°20′12″ S and 36°03′41.9″ E) with an average depth of 3.5 m and Mid lake point (00°21′24″ S and 36°04′53.5″ E) with an average depth of 9.5 m. Fisher's point refers to the point outside the protected area where the fishermen were mainly fishing. The sampling was focused on the northern part of the lake having locations influenced by urban areas, agricultural areas and river mouth. Additionally, it is from the northern part of the lake where fish was being caught by the community.

2.3 | Water and sediment samples

Data on water quality parameters such as pH, dissolved oxygen, conductivity, salinity and temperature was generated through in situ measurement at the selected sites during each sampling occasion. The measurements were conducted using a multiprobe water quality metres and probes (MODEL 4OD, HACH, Malaysia) set at ≈10 cm below the water surface. Sampling was conducted three times on a fortnight basis during the dry season between December 2020 and January 2021. During each sampling occasion, three water samples were collected from the same site at various depths (1 cm below the surface, the mid depth and the bottom) and mixed to make composite samples. A total of nine (9) composite water and a corresponding number of composite sediment samples for heavy metal analysis were collected for the entire study period. The samples were collected from River Njoro mouth, Sewage discharge point and Mid

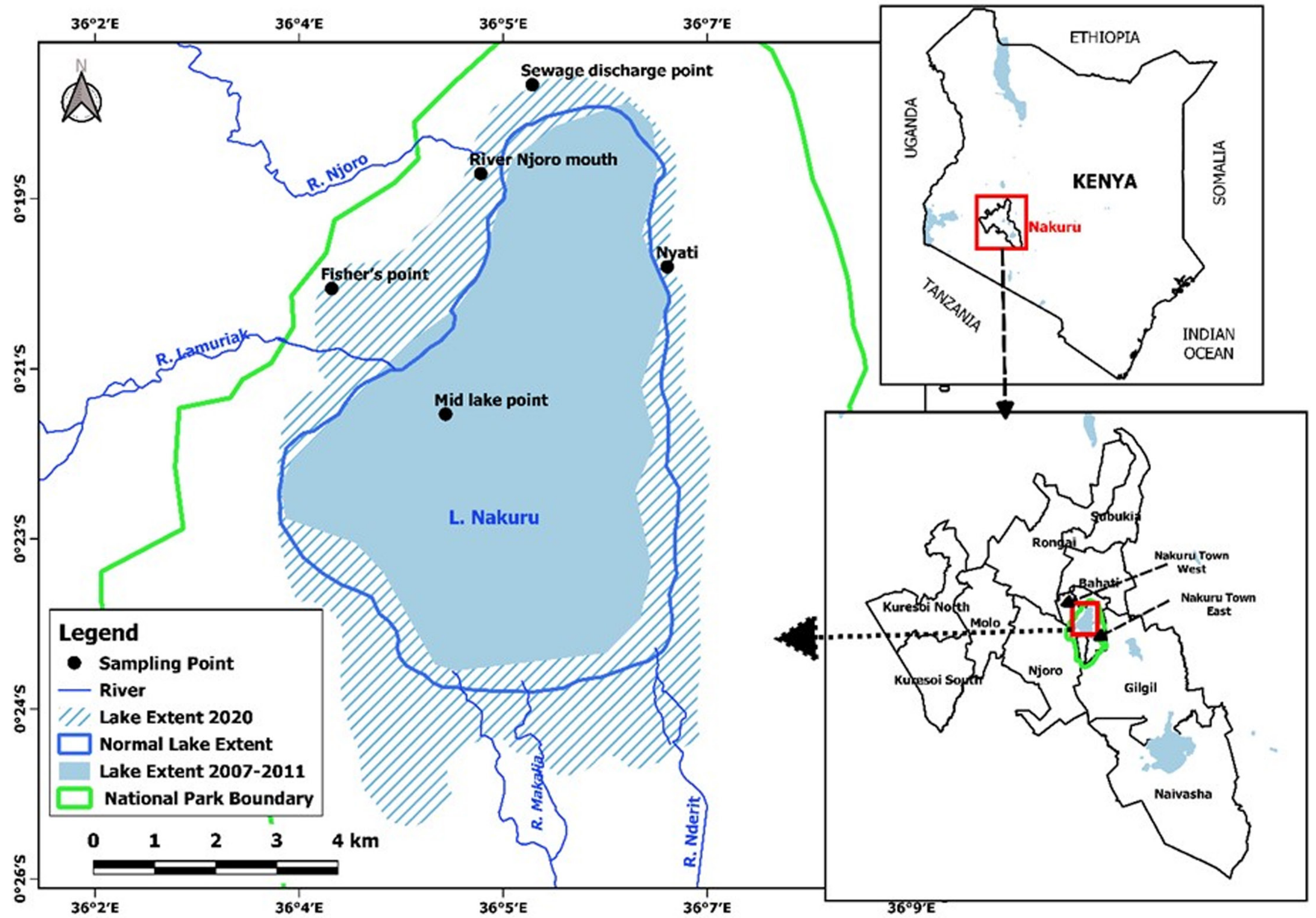

FIGURE 1 Map of Lake Nakuru showing sample site locations.

lake point following standard methods by American Public Health Association (APHA, 2012). At each sampling point, 500 mL of a composite water sample was collected and filtered in situ using a filter pump fitted with Whatman GFC filters of .47 μm size into a pre acid-washed plastic bottle. The sample was then acidified with 2.5 mL of concentrated nitric acid (69%) to avoid precipitation of the metals and adsorption to the surface of the bottles following the standard methods for water and wastewater examination (APHA, 2012).

Following the standard methods by the International Atomic Energy Agency (IAEA, 2003), ≈300 g of a sediment sample was collected from each of the sampling points using a stainless steel Ekman grab sampler and packed in labelled sterile plastic containers. Special care was taken not to obtain the samples from those directly in contact with the surface of the Ekman grab sampler to avoid any form of contamination. The water and sediment samples were transported in a cool box with ice packs to Lake Nakuru Water Quality Testing Laboratory (WQTL) for heavy metal analysis.

2.4 | Fish samples

A total of thirty (30) Nile tilapia specimens were collected with the help of the research team from Kenya Marine and Fisheries Research Institute (KMFRI), Naivasha by setting gill nets of mesh size 2.5 inches around sunset and retrieving them the following morning from the identified sampling sites of Lake Nakuru. Ten (10) fish samples from River Njoro mouth, eleven (11) from Fisher's point, five (5) from Sewage discharge point and four (4) from Nyati. The same sites where sediment and water samples were collected were targeted for fish samples as well. The fish was placed in a cool box and transported to the Department of Biological Sciences, Egerton University for tissue extraction. In the laboratory, the fish skin was removed from both sides of the dorsal part of the fish and muscle tissue extracted using a ceramic knife. The extracted muscle tissue was placed inside plastic vials and then stored at a temperature of −20°C prior to analysis.

2.5 | Heavy metal determination in water, sediment and muscle tissues of Nile tilapia

Following standard methods by APHA (2012), 100 mL of each of the water samples was measured into a clean beaker using a clean measuring cylinder. The sample was then acid digested with 5 mL of 69% analytical grade nitric acid. The digested sample was mixed with 50 mL of double distilled water and immediately heated on a ceramic hot plate stirrer at 440°C in a fume hood for one hour to a final volume of roughly 25 mL. The solution was cooled and filtered using a Whatman filter paper while diluting with double distilled water to a final volume of 100 mL into a volumetric flask ready for heavy metal analysis. Sediment samples were dried to a constant mass in the oven at 100°C after which they were crushed using a mortar and pestle into fine particles. A sub sample (2 g) of the homogenized sediment was weighed using an electronic weighing scale (Model ED 4202S, Sartorius AG, Germany), digested and diluted in a similar manner as for the water sample. The same procedure used for sediments was followed for the fish muscle tissues (2 g) for each of the 30 fish.

Heavy metal concentrations were determined in the digested water (100 mL), sediment (2 g) and fish (2 g) samples by using a direct aspiration atomic absorption spectrophotometer (AAS-S series, United Kingdom) at wavelengths of 357.9, 217, 193.7, 253.7 and 228.8 nm for total chromium (Cr), total lead (Pb), total arsenic (As), total mercury (Hg) and total cadmium (Cd), respectively. Equations obtained from the standard calibration curve were used to calculate heavy metal concentrations. Triplicate analysis of samples was deployed to check instrument accuracy. Both a standard and a blank sample were run to check instrumental drift after every five samples. A serial dilution of a working solution (100 mg/L) made from analytical grade stock solutions (1000 mg/L) acquired from Merck KGaA, Germany was used to prepare standards for instrument calibration. Recovery tests were also conducted using Reference Materials obtained from National Research Council Canada comprising .2 g (dw) of marine sediment PACS-2 and .2 g (dw) of fish protein DORM-3. These were digested and diluted in the same manner as described above for sediments and fish muscle tissues, respectively. The recovery rates obtained were 97% for As, 104% for Hg, 107% for Cr, 102% for Cd and 98% for Pb and these were all in the recommended range.

2.6 | Health risk assessment

The obtained concentrations of the heavy metals in the samples analysed were compared with the recommended reference standards deemed safe for public health such as East African Community (EAC), World Health Organization (WHO) and European Union (EU). The target hazard quotients (THQ) for heavy metal concentrations as per United States Environmental Protection Agency (USEPA, 2012) to evaluate the human health risk of consuming fish contaminated with heavy metals was conducted. The THQ being defined as the ratio between the possible exposure to a substance and the reference dose. The THQs were calculated as described elsewhere (Ngesa et al., 2019; Otachi et al., 2014) as follows:

$$\text{THQ} = \frac{\text{EFr} \times \text{IRFa} \times \text{C}}{\text{RfDo} \times \text{BW} \times \text{AT}}$$

where THQ = non-carcinogenic risk, EFr = exposure frequency (350 days/year) and EDr = exposure duration (30 years) because some of the adverse effects are experienced after a prolonged exposure to heavy metals, IRFa = fish consumption per day (.0123 kg/day) because per capita fish consumption is 4.5 kg/year in Kenya (KMFRI report, 2017), C = concentration of a pollutant in edible part of fish (milligrams per kilogram wet weight (ww)), RfDo = reference dose, oral (milligrams per kilogram per day, according to the updated 2017 Regional Screening Level (RSL)) in the fish ingestion table (USEPA, 2017). The RfDo for arsenic, for example, is .0003 mg/kg/day, chromium is .003 mg/kg/day, lead is .004 mg/kg/day and mercury is .0001 mg/kg/day. BWa is the body weight of an adult male (63.9 kg) and female (61.8 kg) for Kenya (WorldData, n.d), AT is the averaging time for non-carcinogens (365 days/year).

2.7 | Data analysis

All data collected were stored in Microsoft office excel. Statistical tests were done using R statistical software version 3.6.3. The concentrations of heavy metals in the analysed samples were presented as mean with standard deviation (mean ± standard deviation). One-way analysis of variance was used to test the differences in mean concentrations of the selected water quality parameters and heavy metals in the different lake matrices (water, sediments and fish) across sampling sites. All statistical tests were performed at a significance level (α) of .05.

3 | RESULTS

3.1 | Characteristics of fish samples

A total of 30 fish were collected for heavy metal analysis. The mean total length was 20.7 ± 3.2 cm (Mean ± SD), range was 11.7 (14.3–26.0 cm) with a sample variance of 10.1 and the mean weight was 179.8 ± 76.1 g (Mean ± SD), with a range of 303 (60.1–363.1 g) with a sample variance of 5796.8.

3.2 | Water quality parameters

A summary of water quality parameters monitored in the entire study are presented in Table 1. The electrical conductivity measured in the water column during this study ranged between 4470 and 5226 μS/cm and was generally low for such a saline system. The pH, dissolved oxygen, temperature and salinity ranged from 9.52 to 9.72, 4.58 mg/L to 8.62 mg/L, 23.40°C to 25.7°C and 2.39‰ to 2.81‰, respectively. None of the differences in mean pH, dissolved oxygen, temperature, electrical conductivity and salinity levels across the different sampling points were significant $p > .05$ (one-way ANOVA, pH ($F_{2,6} = .6$, $p = .58$), dissolved oxygen ($F_{2,6} = 3.05$, $p = .12$), temperature ($F_{2,6} = 1.71$, $p = .26$), conductivity ($F_{2,6} = .08$, $p = .93$) and salinity ($F_{2,6} = .10$, $p = .90$)) Tables 2 and 3.

TABLE 1 Means and ranges of water quality parameters recorded for Lake Nakuru during the entire study period compared with previous studies and similar lakes ($n=9$, superscripts indicate literature sources).

Source parameter	River Njoro mouth	Sewage discharge point	Mid lake point	Previous studies	L. Naivasha
Temperature (°C) mean	24.9 ± .9	23.7 ± .6	24.6 ± .7		
pH range	9.59–9.71	9.58–9.72	9.52–9.69		9.15[e], 9[f]
Dissolved oxygen (mg/L) mean	7.5 ± 1.5	5.5 ± .8	6.9 ± .5	17[b]	
Conductivity (μs/cm) mean	4758.9 ± 350.5	4760.0 ± 384.9	4856.7 ± 321.4	10,000–160,000[a]	
Salinity (‰) mean	2.6 ± .2	2.5 ± .2	2.6 ± .2	18[b], 15.37[c], 29.3[d]	

[a]Vareschi (1982).
[b]Oduor and Schagerl (2007).
[c]Raini (2009).
[d]Jirsa et al. (2013).
[e]Ochieng et al. (2007).
[f]Otachi et al. (2014).

TABLE 2 Heavy metal concentrations for water samples in comparison with the WHO maximum permissible levels, KEBS, NEMA water quality standards and previous studies (mg/L) ($n=9$, superscripts indicate the literature sources).

Element	Water (mg/L)	LOD	WHO	KEBS	NEMA	Previous studies
Arsenic	BDL	.001	.01	.01	.01	
Cadmium	BDL	.02	.003	.01	.01	
Chromium	.150	.01	.05	.05	NG	
Lead	.013	.004	.01	.01	.01	.01[a], .29[b], .02[c], .0002[d], .002[e]
Mercury	.004	.0005	.006	.001	.001	.003[e], 2.48[f]

Abbreviations: BDL, Below detection limit; KEBS, Kenya Bureau of Standards (2014); NEMA, National Environment Management Authority (2006); NG, Not given; WHO, World Health Organization (2011).
[a]Tenai et al. (2016).
[b]Ochieng et al. (2007).
[c]Nelson et al. (1998).
[d]Barasa et al. (2017).
[e]Yang et al. (2017).
[f]Mavura and Wangila (2003).

3.3 | Heavy metal concentrations in water

Among the five heavy metals measured, arsenic and cadmium were below detection in all the water samples for all sites. The order of concentration for heavy metals in water samples was Cr > Pb > Hg (Figure 2). There were no significant differences in mercury concentrations across sites $p > .05$ (One-way ANOVA, ($F_{2,6} = .02$, $p = .98$)) whereas chromium and lead showed significant differences across sites $p < .05$. A post hoc using the Tukey HSD test showed that the mean chromium concentration for River Njoro mouth was significantly greater than that of Sewage discharge point and Mid lake point. Similarly, the mean chromium concentration of Mid lake point was significantly lower than that of Sewage discharge point $p < .05$. The mean lead concentration at River Njoro mouth was significantly greater than that of Sewage discharge point and Mid lake point $p < .05$.

3.4 | Heavy metal concentrations in sediments

The order of concentration for heavy metals in sediment samples was Pb > As > Cr > Hg (Figure 3) Cadmium was not detected in any of the sediment samples. There were no significant differences in mean chromium and mercury levels across sites $p > .05$ (One-way ANOVA, chromium ($F_{2,6} = 1.05$, $p = .41$) and mercury ($F_{2,6} = .54$, $p = .61$)) whereas arsenic and lead showed significant differences across sites $p < .05$. A post hoc using the Tukey HSD test revealed that the arsenic concentration of River Njoro mouth was significantly greater than that of Sewage discharge point $p < .05$. Likewise, the lead concentration of Sewage discharge point was greater than that of River Njoro mouth and Mid lake point. Similarly, the lead concentration of Mid lake point was greater than that of River Njoro mouth $p < .05$. The mean concentrations of all heavy metals considered in this study were compared with

TABLE 3 Concentrations of heavy metals in sediment samples from Lake Nakuru in comparison with different sediment quality guidelines, previous studies and other lakes ($n = 9$, superscripts indicate literature sources).

Element	Sediment (mg/kg)	LEL	TEC	SEL	Shale	Previous studies
Arsenic	15.45	6.0	9.79	33.0	13	.35[d], 6.1[e]
Cadmium	ND	.6	.99	10.0	.3	
Chromium	8.21	26.0	43.4	110.0	90	57.85[e], 23.8[d]
Lead	18.30	31.0	35.8	250.0	20	11.89[a], 14.36[b], 16[c], .43[d]
Mercury	.22	.2	.18	2.0	.4	3.06[f]

Note: The sediment quality guidelines are given in mg/kg (Turekian & Wedepohl, 1961); Persaud et al. (1993); Doyle et al. (2003); Buchman, (2008).

Abbreviations: LEL, lowest effect level in sediment; SEL; severe effect level in sediment; TEC, threshold effect concentration in sediment.

[a]Mavura and Wangila (2003).

[b]Ochieng et al. (2007).

[c]Barasa et al. (2017).

[d]Tenai et al. (2016).

[e]Jirsa et al. (2013).

[f]Mavura and Wangila (2003).

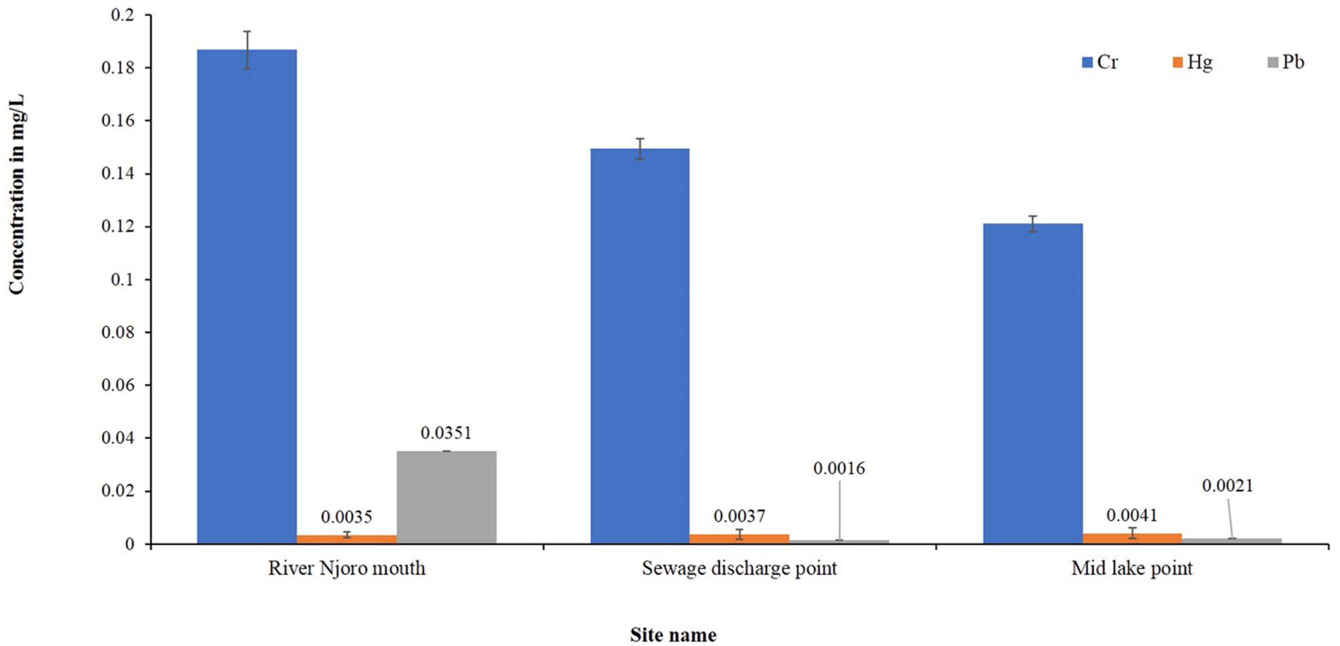

FIGURE 2 Heavy metal concentrations in water samples for different sampling sites.

the sediment quality guidelines that is threshold effect concentration (TEC), lowest effect level (LEL), severe effect level (SEL) as well as Shale. Lead and chromium had concentrations below LEL, TEC, SEL and Shale values of sedimentary rocks. However, mercury had concentrations similar to LEL and TEC whereas arsenic mean concentration in sediments exceeded LEL, TEC and Shale. Therefore, regarding Cr and Pb, the sediments of Lake Nakuru did not demonstrate any sign of pollution considering the sediment quality guidelines by Turekian and Wedepohl (1961). However, the concentrations of As and Hg obtained in the sediments of Lake Nakuru indicated anthropogenic related pollution given that they exceeded the sediment quality guideline values.

3.5 | Heavy metal concentrations in muscle of Nile tilapia

As the case with water and sediment samples, cadmium was not detected in any of the fish samples. The order of concentration for heavy metals in the muscle tissues of Nile tilapia was Cr > Pb > As > Hg (Table 4). There was no significant difference in mean concentrations of mercury and lead across sites $p > .05$ (One-way ANOVA, mercury ($F_{3,26} = 2.57$, $p = .07$) and lead ($F_{3,26} = 1.83$, $p = .17$)) whereas arsenic and chromium showed significant differences across sites $p < .05$. A post hoc using the Tukey HSD test revealed that the mean arsenic concentration of fish samples caught

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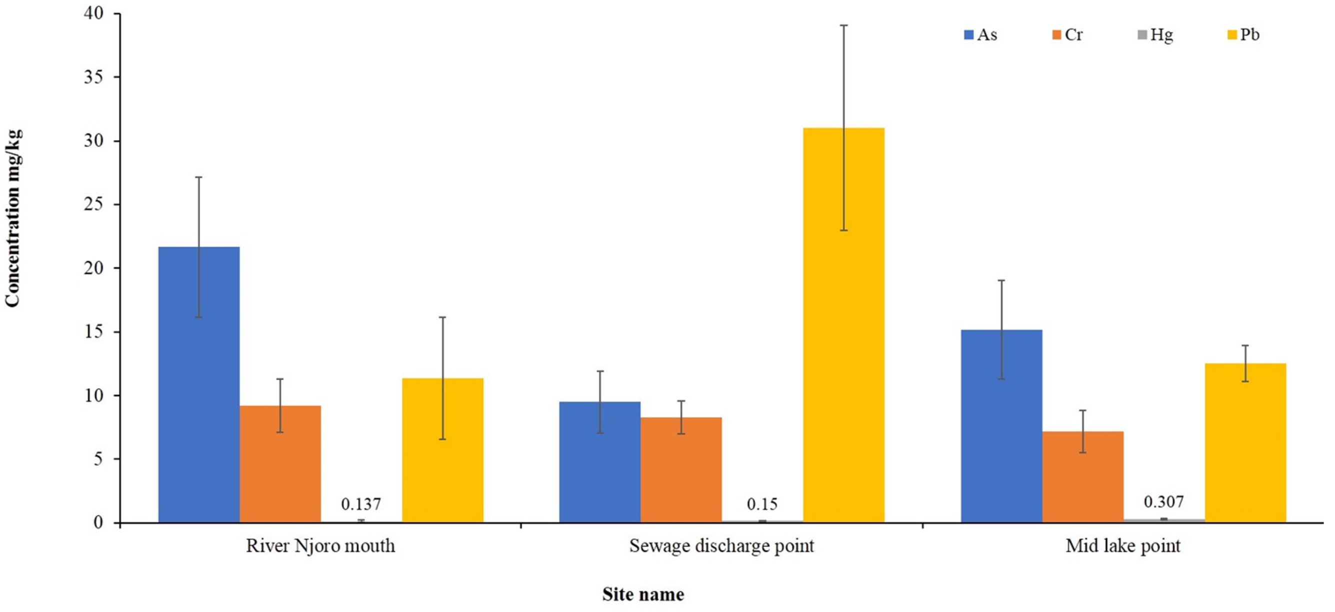

FIGURE 3 Heavy metal concentrations in sediments for different sampling sites.

TABLE 4 Mean concentrations of heavy metals in muscle of Nile tilapia samples caught from four sites of Lake Nakuru (mg/kg dw).

Site	RNM	SDP	FP	NYATI
Element				
Arsenic	1.85 ± .14	.41 ± .02	2.11 ± .17	<.001
Cadmium	<.02	<.02	<.02	<.02
Chromium	4.17 ± 2.80	3.7 ± .96	13.06 ± 1.92	6.65 ± 2.48
Lead	9.95 ± .23	4.06 ± .09	6.05 ± 2.50	9.30 ± 1.47
Mercury	.12 ± .03	.35 ± .06	.13 ± .02	<.0005
N	10	5	11	4

Abbreviations: FP, Fisher's point; N, number of samples; RNM, River Njoro mouth; SDP, sewage discharge point.

from River Njoro mouth was significantly greater than that of fish caught from Sewage discharge point. Similarly, the mean arsenic concentration of fish samples from Fisher's point was significantly greater than that of Sewage discharge point $p < .05$. The mean chromium concentration of fish samples of Fisher's point was significantly greater than that of fish caught from Sewage discharge point $p < .05$.

3.6 | Heavy metal pollution and safety of Nile tilapia

The mean heavy metal concentrations obtained in the fish samples from Lake Nakuru in this study were computed and compared with the maximum permissible limits for different bodies on a national and international level. Chromium and lead levels in the muscle of Nile tilapia exceeded the FAO and EU maximum permissible limits in fish and fishery products. The target hazard quotients for heavy metals were also computed. Arsenic had the highest THQ in both male and female human fish consumers followed by chromium, lead and lastly mercury. The THQs for all metals were slightly higher for female when compared to male consumers.

4 | DISCUSSION

4.1 | Water quality parameters

Electrical conductivity and salinity were unusually lower for such a saline system with values of 4470–5226 µs/cm and 2.3‰–2.8 ‰, respectively, measured during the present study period. According to classification of lakes based on conductivity by Talling and Talling (1965), the current conductivity for Lake Nakuru falls within a range of 600–6000 µS/cm, which is linked to moderately saline lakes. In the classification, lakes with a conductivity of <600 µS/cm are fresh water whereas those with a conductivity >6000 µS/cm are saline lakes. The electrical conductivity values obtained in this study were lower than what was reported by other earlier studies in the same lake such as Vareschi (1982); Kairu (1994), Leichtfried and Shivoga (1995); Nelson et al. (1998); Ochieng et al. (2007);

Oduor and Schagerl (2007) and Raini (2009). The comparatively low electrical conductivity and salinity values obtained in the different studies could be attributed to the difference in sampling seasons, sites and time. Ndetei and Muhandiki (2005) pointed out that conductivity tends to decrease during the rainy season most especially in the dynamic saline Rift Valley lakes of Kenya including Nakuru, Elementeita and Magadi. The differences in salinity levels could be attributed to dilution arising from the present increase in lake water levels.

The pH of the lake water in this study ranged between 9.52 and 9.72. These pH values were comparable to what has been reported for another freshwater lake. The mean pH of 9.6 obtained in this study is slightly lower than what was reported by an earlier study in the same lake. The pH range obtained in this study indicated that Lake Nakuru was tending towards a freshwater lake as the pH of alkaline lakes is reported to be >10 (Ochieng et al., 2007). The survival of freshwater fish species like Nile tilapia in this originally known saline lake could also justify this.

There was no spatial variation in the level of dissolved oxygen across sites. Dissolved oxygen ranged between 4.7 and 9.0 mg/L with the highest amount being recorded at the mouth of River Njoro. This could be attributed to the clear fresh water coming into the lake after most of the impurities have settled thus allowing for free circulation of oxygen from the atmosphere. However, this study reported a lower mean dissolved oxygen concentration (6.6 mg/L) when compared to a previous study. The differences could be attributed to variations in sampling time as well as season. Furthermore, dilution could have led to a significant decline in abundance of *Arthrospira fusiformis* which had dominated the lake and was the main food of lesser flamingos which migrated as a result. *A. fusiformis* is known to form a high algal crop due to its high photosynthetic capacity with a consequent production of oxygen (Schagerl et al., 2015). This could also have led to the low levels of dissolved oxygen recorded in the present study.

4.2 | Heavy metal concentrations in water

Arsenic and cadmium were not detected in any of the water samples and this agreed with the findings of Barasa et al. (2017) who did not record the two elements in their study in Lake Nakuru. They associated the finding to the increase in water levels in the saline Rift Valley lakes of Kenya. However, the finding regarding arsenic absence in water samples was contrary to the findings of Tenai et al. (2016) and Yang et al. (2017) who detected arsenic in the same lake. The known sources of cadmium into the environment include wastewater discharge, industrial air emissions as well as the extensive application of phosphate fertilizers that end up in aquatic systems (Kim et al., 2015). It was interesting cadmium was not detected in any of the samples given that the Lake Nakuru catchment is largely agricultural. This could be because cadmium was not present in a bioavailable form. Cadmium tends to form stable complexes with organic matter (Kubier et al., 2019). According to Berrow and Mitchell (1980), 99% of the metal content of the soil solution might be present in complexed forms.

The mean Cr concentration of .15 mg/L obtained in this study was higher than that reported by Nelson et al. (1998), Ochieng et al. (2007) and Tenai et al. (2016) in the same lake. The relatively high concentration of chromium in all sites sampled in this study could be attributed to discharge of wastes rich in Cr more so through the inflowing rivers like River Njoro. The main pathway of pollution of aquatic systems with chromium is discharge of improperly treated industrial waste and direct discharge of waste waters into waterways from industries such as tanneries, textile and electroplating (Kimbrough et al., 1999; Reid, 2011). Additionally, the level of Cr obtained in this study was contrary to the findings of Yang et al. (2017) who did not detect chromium in the water samples from the same lake. However, Barasa et al. (2017) reported a higher Cr concentration in water of Lake Nakuru than the current study. The differences in findings regarding Cr for Barasa et al. (2017) and Yang et al. (2017) could be attributed to the differences in sampling times within the years and sites as well. Comparing the heavy metal concentrations obtained in this study with World Health Organization (WHO, 2011) and Kenya Bureau of Standards (KEBS, 2014) permissible limits, chromium exceeded the benchmark values of both WHO and KEBS. This could indicate that Lake Nakuru water was contaminated with chromium at the time of sampling. The relatively high Cr level obtained even at the Mid lake point could justify that indeed the lake was polluted with Cr.

The mean lead level of .013 mg/L obtained in this study was comparable to that obtained by Tenai et al. (2016). Higher lead concentrations were reported by Ochieng et al. (2007) and Nelson et al. (1998) in the same lake. However, Barasa et al. (2017) and Yang et al. (2017) reported lower concentrations of lead in water samples from Lake Nakuru. The lead concentrations were within WHO, KEBS and NEMA permissible limits in water.

A mean mercury concentration of .004 mg/L was obtained in the water samples in this study. However various studies conducted in Lake Nakuru have not considered studying mercury levels in water except for a few such as Yang et al. (2017) who obtained Hg concentration comparable to the current study. On the contrary, Mavura and Wangila (2003) reported a higher mean Hg concentration in water samples from the same lake. The mean mercury concentration obtained in this study was within WHO limits but exceeded KEBS and NEMA permissible limits in water.

4.3 | Heavy metal concentrations in sediments

The mean lead concentration (18.30 mg/kg dw) obtained in this study was higher than what Mavura and Wangila (2003), Ochieng et al. (2007) and Barasa et al. (2017) obtained in Lake Nakuru. More still, the mean Pb concentration in this study was far much higher than what was reported by Tenai et al. (2016) in the same lake. The relatively high lead concentration in the present study despite the increased water levels could indicate a continued input of lead into the lake with a consequent accumulation into the sediments.

The mean arsenic concentration (15.45 mg/kg dw) obtained in the sediments of Lake Nakuru in this study was higher than what was reported by Tenai et al. (2016) and Barasa et al., 2017 who did not detect arsenic in sediment samples from the same lake. Similarly, Jirsa et al. (2013) reported a lower mean arsenic concentration in Lake Nakuru sediments. The observed trend of arsenic levels compared to earlier studies could indicate a continued input of the pollutant into the lake. The probable sources of arsenic into the Lake could be linked to pesticide usage in the Lake Nakuru catchment as well as atmospheric deposition (Morin & Calas, 2006).

The mean chromium concentration (8.21 mg/kg dw) obtained in this study was much lower than what Jirsa et al. (2013) and Tenai et al. (2016) obtained in Lake Nakuru. However, Mavura and Wangila (2003), Ochieng et al. (2007) and Barasa et al. (2017) reported lower concentrations of Cr in sediments of Lake Nakuru. The variations could be attributed to differences in study sites and sampling seasons. The observed levels of Cr in sediments could be attributed to anthropogenic input more so municipal and domestic discharges from the nearby Nakuru town (Mavura & Wangila, 2003).

The mean mercury concentration (.22 mg/kg dw) reported in the current study was lower than values reported by Mavura and Wangila (2003) in sediments of the same lake. However, Barasa et al., 2017 did not detect mercury in all sediment samples considered in their study. The Hg concentration in the sediments could indicate a reduced input of the metal into the lake comparing the finding of this study to Barasa's finding and differences in sampled sites. The variations in results for heavy metal concentration in sediment samples for the current study and previous ones could be linked to difference in sampling time, sites and seasons.

4.4 | Heavy metal concentrations in muscle of Nile tilapia

The Cr level (7.01 mg/kg dw) obtained in this study was higher than what Mavura and Wangila (2003) reported in Tilapia grahami (*Alcalicus grahami*) from the same lake. Unfortunately, many earlier studies that studied heavy metal contamination in fish of Lake Nakuru such as Koeman et al. (1972) and Kairu (1999) did not include chromium. Elsewhere, this study recorded lower Cr levels than what Ngesa et al. (2019) reported in the muscle of *Enteromius paludinosus* in Lake Naivasha. The relatively high levels of chromium in Nile tilapia of Lake Nakuru could be attributed to discharge of improperly treated industrial waste and direct discharge of waste waters into the lake mainly through the inflowing rivers (Reid, 2011). This could be justified by the relatively high levels of chromium in water samples obtained from River Njoro mouth as compared to the other sites.

The mean lead concentration obtained in the muscle tissues of Nile tilapia (5.84 mg/kg dw) in this study was higher than what was reported by Mavura and Wangila (2003) in Tilapia grahami (*Alcalicus grahami*) of Lake Nakuru (Table 5). Unfortunately, the fishery being a recent activity in Lake Nakuru, not so many studies have investigated heavy metal pollution in fish. Elsewhere, Otachi et al. (2015), reported lower mean Pb concentration in the muscle of *Oreochromis leucostictus* from Lake Naivasha compared to the present study. The high levels of Pb in the fish muscle indicates high levels in the lake and these could be attributed to the automobile batteries disposed of near the lake and vehicular emission (Mavura & Wangila, 2003). This finding concurs with the findings of Yabe et al. (2010) who found out that heavy metal pollution in different environmental matrices in Africa had risen tremendously to levels exceeding permissible limits and pointed out lead as one of the metals that are widespread.

The mean mercury level (.15 mg/kg dw) obtained in this study was lower than what was reported by earlier studies such as Mavura and Wangila (2003) in fish from the same lake. On the contrary, the mercury concentration of this study was higher than what was reported by Koeman et al. (1972) and Kairu, 1999 in Tilapia grahami (*Alcalicus grahami*) caught from Lake Nakuru. Elsewhere, the mean mercury concentration of this study was higher than what Hollamby et al. (2004) reported in Nile tilapia from Lakes: Mburo and Victoria, Uganda.

In comparison to other heavy metals considered in this study, the metalloid As concentration in fish tissues has not been widely studied. However, the mean arsenic concentration (1.46 mg/kg dw) obtained in this study was higher than what Koeman et al. (1972) and Kairu (1999) obtained in Tilapia grahami (*Alcalicus grahami*) from Lake Nakuru (Table 5). This finding shows an increased input of arsenic into the lake over the years with a consequent bioaccumulation in fish given that baseline studies recorded relatively lower levels.

4.5 | Heavy metal pollution and safety of Nile tilapia

The target hazard quotients (THQs) for Pb, Cr, Hg and As exceeded the benchmark THQ of 1 (USEPA, 2012) indicating a potential health risk to consumers of Nile tilapia from Lake Nakuru. The mean lead (Pb) and chromium (Cr) levels in the muscle of Nile tilapia obtained in this study were above the WHO/FAO and EU maximum permissible levels for fish and fishery products. The consumers of this fish are prone to body organ and system damage for example kidney, liver, reproductive system, nervous system, urinary system and immune system, respiratory and gastrointestinal impairment, hematologic disorders as well as developmental abnormalities (Blacksmith Institute, 2012; Njuguna et al., 2017; WHO, 2010) Table 6.

5 | CONCLUSIONS

The levels of water quality parameters from Lake Nakuru were generally lower than the levels reported by earlier studies. The present study concludes that dilution resulting from increased water levels has changed the lake from saline towards fresh water. Chromium levels were above the recommended standards in water samples, arsenic exceeded the sediment quality guidelines whereas chromium

TABLE 5 Heavy metal concentrations in muscle of Nile tilapia samples (n = 30) in comparison with FAO maximum permissible levels and EU and EAC fish and products quality standards (mg/kg) for food safety.

Element	Fish (mg/kg dw)	FAO (mg/kg)	EU	EAC	Previous studies	Lake Naivasha	Lakes Mburo and Victoria
Arsenic	1.46	–	–	.1	.086[g], .03[h]		
Cadmium	ND	.05	.05[a]	.3			
Chromium	7.01	.05	.05[a]	–	1.05[d]	22.09[e]	
Lead	5.84	.2	.3[c]	.3	3.22[d]	.024[f]	
Mercury	.15	.5	.5[b]	.5	3.34[d], .016[g], <.01[h]		.01[i]

Abbreviations: (–), value not provided; FAO, Food and Agricultural Organization; East African Community (EAC, 2016); World Health Organization (WHO, 2003).

[a]European Union (EU, 2006).

[b]EU (2011).

[c]EU (2015).

[d]Mavura and Wangila (2003) for *Tilapia graham*.

[e]Ngesa et al. (2019).

[f]Otachi et al. (2015) in *O. leucostictus*.

[g]Koeman et al. (1972).

[h]Kairu (1999).

[i]Hollamby et al. (2004).

TABLE 6 Target hazard quotients (THQs) for male and female human fish consumers for the four heavy metals detected in present study.

Element	Consumer	Arsenic	Chromium	Lead	Mercury
THQ	Males	26.53	13.95	10.00	8.17
	Females	27.91	14.68	10.52	8.60

and lead exceeded the WHO and KEBS permissible limits for fish and fishery products. The present study concludes that Nile tilapia from Lake Nakuru is not safe for human consumption. Its safety is limited by elevated levels of chromium and lead as well as THQs exceeding 1 for all metals. Since the water quality status has indicated that the lake is tending towards fresh water, this study recommends an assessment of all the abiotic and biotic parameters of the lake and a possible reclassification of the lake. Given that the findings of this study indicate that Lake Nakuru fish is not safe for human consumption, the present study recommends an immediate ban on fish harvesting and consumption from Lake Nakuru as well as a policy intervention on fishery and pollution management.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available on request from the corresponding author.

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REFERENCES

American Public Health Association (APHA). (2012). *Standard methods for the examination of water and wastewater* (22nd ed., p. 724). American Public Health Association, American Water and Water works Association and Water Environment Federation.

Barasa, M., Mbaria, J., Muchem, G., Gakuya, F., Kariuki, E., & Wamiti, W. (2017). Ecological risk assessment of heavy metals and water bird distribution in rift valley lakes, Kenya. *Journal of Ecology and the Natural Environment*, *9*(3), 30–44. https://doi.org/10.5897/JENE2017.0628

Berrow, M. L., & Mitchell, R. L. (1980). Location of trace elements in soil profiles: Total and extractable contents of individual horizons. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, *71*(2), 103–121. https://doi.org/10.1017/S0263593300013547

Blacksmith Institute. (2012). *The World's worst pollution problems: Assessing health risks at hazardous waste sites*. Blacksmith Institute https://www.worstpolluted.org/files/FileUpload/files/WWPP2012.pdf

Buchman, M. F. (2008). *NOAA screening quick reference tables, NOAA OR and R report 08-1*. National Oceanic and Atmospheric Administration. Office of Response and Restoration Division.

Doyle, J., Solberg, T., Tiefenthaler, J., O'Brien, G., Behnke, H. F., Poulson, H. D., & Willett, S. D. (2003). *Consensus-based sediment quality guidelines; recommendations for use and application interim guidance*. Wisconsin Department of Natural Resources.

EAC. (2016). Draft East African Standard DEAS 899: 2016. https://members.wto.org/crnattachments/2016/TBT/UGA/16-3796_00_e.pdf

EU. (2006). *Commission regulation (EC) No 1881/2006: Setting maximum levels for certain contaminants in foodstuffs. Official Journal of the European Union*. L 364/5 (2006).

EU. (2011). *Commission regulation (EC) No 420/2011 of 29 April 2011 amending regulation (EC) No 1881/2006 setting maximum levels for certain contaminants in foodstuffs. Official Journal of the European Union*. L 111/3 (2011).

EU. (2015). *Commission regulation (EC) 2015/1005 of 25 June 2015 amending regulation (EC) No 1881/2006 as regards maximum levels of lead in certain foodstuffs. Official Journal of the European Union*. L 161/9 (2015).

Hazrat, A., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, *2019*, 1–14. https://doi.org/10.1155/2019/6730305

Hollamby, S., Afema-Azikuru, J., Sikarskie, J. G., Kaneene, J. B., Bowerman, W. W., Fitzgerald, S. D., & Rumbeiha, W. K. (2004). Mercury and persistent organic pollutant concentrations in African fish eagles, marabou storks, and Nile tilapia in Uganda. *Journal of Wildlife Diseases*, *40*(3), 501–514. https://doi.org/10.7589/0090-3558-40.3.501

IAEA. (2003). *Collection and preparation of bottom sediment samples for analysis of radionuclides and trace elements* (p. 130). International Atomic Energy Agency technical document No. 1360.

Iradukunda, P., Sang, J. K., Nyadawa, M. O., & Maina, C. W. (2020). Sedimentation effect on the storage capacity in Lake Nakuru, Kenya. *Journal of Sustainable Research in Engineering*, *5*(3), 149–158.

Jirsa, F., Gruber, M., Stojanovic, A., Omondi, S. O., Mader, D., Körner, W., & Schagerl, M. (2013). Major and trace element geochemistry of Lake Bogoria and Lake Nakuru, Kenya, during extreme draught. *Geochemistry*, *73*(3), 275–282. https://doi.org/10.1016/j.chemer.2012.09.001

Junjiro, N., & Masahisa, N. (2005). Current status and challenges in managing the upper rural areas of world Lake basins: Preliminary implications from the GEF-project Lake briefs. In E. O. Odada, D. O. Olago, W. Washington, M. Ntiba, S. Wandiga, N. Gichuki, & H. Oyieke (Eds.), *Proceedings*, *11th world Lake conference* (Vol. *1*, pp. 40–47). ILEC.

Kairu, J. K. (1994). Pesticide residues in birds at Lake Nakuru, Kenya. *International Journal of Salt Lake Research*, *3*(1), 31–48. https://doi.org/10.1007/BF01990640

Kairu, J. K. (1999). Organochlorine pesticide and metal residues in a cichlid fish, tilapia, Sarotherodon (= tilapia) *alcalicus grahami* Boulenger from Lake Nakuru, Kenya. *International Journal of Salt Lake Research*, *8*(3), 253–266. https://doi.org/10.1023/A:1009037417751

KEBS. (2014). Kenya Standard Potable water – Specification. KS EAS 12:2014, ICS 13.060.20. First Edition.

Kim, H. S., Kim, Y. J., & Seo, Y. R. (2015). An overview of carcinogenic heavy metal: Molecular toxicity mechanism and prevention. *Journal of Cancer Prevention*, *20*(4), 232–240. https://doi.org/10.15430/JCP.2015.20.4.232

Kimbrough, D. E., Cohen, Y., Winer, A. M., Creelman, L., & Clayton Mabuni, C. (1999). A critical assessment of chromium in the environment. *Critical Reviews in Environmental Science and Technology*, *29*(1), 1–46. https://doi.org/10.1080/10643389991259164

Koeman, J. H., Pennings, J. H., De Goeij, J. J. M., Tjioe, P. S., Olindo, P. M., & Hopcraft, J. (1972). A preliminary survey of the possible contamination of Lake Nakuru in Kenya with some metals and chlorinated hydrocarbon pesticides. *Journal of Applied Ecology*, *9*(2), 411–416. https://doi.org/10.2307/2402441

Kubier, A., Wilkin, R. T., & Pichler, T. (2019). Cadmium in soils and groundwater: A review. *Applied Geochemistry*, *108*, 1–16. https://doi.org/10.1016/j.apgeochem.2019.104388

Kundu, R., Musa, S. M., Mulanda, A. C., & Lusweti, D. (2014). Ecotoxicological assessment of pollutants in Lake Victoria fishery, Kenya: Proof of fish consumption? https://www.oceandocs.org/handle/1834/7345

Leichtfried, M., & Shivoga, W. A. (1995). The Njoro River-Lake Nakuru Ecotonal system in Kenya. *Jahresbericht Biological Station, Lunz*, *15*, 67–77.

Mavura, W. J., & Wangila, P. T. (2003). The pollution status of Lake Nakuru, Kenya: Heavy metals and pesticide residues, 1999/2000. *African Journal of Aquatic Science*, *28*(1), 13–18. https://doi.org/10.2989/16085914.2003.9626594

Morin, G., & Calas, G. (2006). Arsenic in soils, mine tailings, and former industrial sites. *Elements*, *2*(2), 97–101. https://doi.org/10.2113/gselements.2.2.97

Munguti, J. M., Nairuti, R., Iteba, J. O., Obiero, K. O., Kyule, D., Opiyo, M. A., Abwao, J., Kirimi, J. G., Outa, N., Muthoka, M., Githukia, C. M., & Ogello, E. O. (2022). Nile tilapia (*Oreochromis niloticus* Linnaeus, 1758) culture in Kenya: Emerging production technologies and socio-economic impacts on local livelihoods. *Aquaculture, Fish and Fisheries*, *2*, 265–276. https://doi.org/10.1002/aff2.58

Murtala, B. A., Abdul, W. O., & Akinyemi, A. A. (2012). Bioaccumulation of heavy metals in fish (*Hydrocynus forskahlii*, *Hyperopisus bebe occidentalis* and *Clarias gariepinus*) organs in downstream Ogun coastal water, Nigeria. *Journal of Agricultural Science*, *4*(11), 51–59. https://doi.org/10.5539/jas.v4n11p51

Ndetei, R., & Muhandiki, V. S. (2005). Mortalities of lesser flamingos in Kenyan Rift Valley saline lakes and the implications for sustainable management of the lakes. *Lakes & Reservoirs: Research & Management*, *10*(1), 51–58. https://doi.org/10.1111/j.1440-1770.2005.00255.x

Nelson, Y. M., Thampy, R. J., Motelin, G. K., Raini, J. A., DiSante, C. J., & Lion, L. W. (1998). Model for trace metal exposure in filter-feeding flamingos at alkaline Rift Valley Lake, Kenya. *Environmental Toxicology and Chemistry: An International Journal*, *17*(11), 2302–2309. https://doi.org/10.1002/etc.5620171122

NEMA. (2006). The Environmental Management and Coordination, (Water Quality) Regulations 2006. https://www.betacare.co.ke/images/she%20policies/Water%20Quality%20Regulations%20ken84962.pdf

Ngesa, E. A., Otachi, E. O., & Kitaka, N. K. (2019). Levels of heavy metals in the straightfin barb *Enteromius paludinosus* (Peters 1852) from river Malewa, Naivasha, Kenya. *Environmental Monitoring and Assessment*, *191*(5), 1–12. https://doi.org/10.1007/s10661-019-7457-5

Njuguna, S. M., Yan, X., Gituru, R. W., Wang, Q., & Wang, J. (2017). Assessment of macrophyte, heavy metal, and nutrient concentrations in the water of the Nairobi River, Kenya. *Environmental*

Monitoring and Assessment, *189*(9), 1–14. https://doi.org/10.1007/s10661-017-6159-0

Ochieng, E. Z., Lalah, J. O., & Wandiga, S. O. (2007). Analysis of heavy metals in water and surface sediment in five rift valley lakes in Kenya for assessment of recent increase in anthropogenic activities. *Bulletin of Environmental Contamination and Toxicology*, *79*(5), 570–576. https://doi.org/10.1007/s00128-007-9286-4

Odada, E., Raini, J., & Ndetei, R. (2004). Experiences and lessons learned brief, Lake Nakuru. https://www.semanticscholar.org/paper/Lake-Nakuru%3A-experience-and-lessons-learned-brief-Odada-Raini/7e6ad81b8d594f78e5b7262b2d2b029e72f49767

Oduor, S. O., & Schagerl, M. (2007). Temporal trends of ion contents and nutrients in three Kenyan Rift Valley saline-alkaline lakes and their influence on phytoplankton biomass. *Hydrobiologia*, *584*, 59–68. https://doi.org/10.1007/978-1-4020-6399-2_6

Otachi, E. O., Körner, W., Avenant-Oldewage, A., Fellner-Frank, C., & Jirsa, F. (2014). Trace elements in sediments, blue spotted tilapia Oreochromis leucostictus (Trewavas, 1933) and its parasite Contracaecum multipapillatum from Lake Naivasha, Kenya, including a comprehensive health risk analysis. *Environmental Science and Pollution Research*, *21*(12), 7339–7349.

Otachi, E. O., Plessl, C., Körner, W., Avenant-Oldewage, A., & Jirsa, F. (2015). Trace elements in water, sediments and the elongate tigerfish *Hydrocynus forskahlii* (Cuvier 1819) from Lake Turkana, Kenya including a comprehensive health risk analysis. *Bulletin of Environmental Contamination and Toxicology*, *95*(3), 286–291. https://doi.org/10.1007/s00128-015-1603-8

Pandey, V. C., & Singh, V. (2019). Exploring the potential and opportunities of current tools for removal of hazardous materials from environments. In *Phytomanagement of Polluted Sites* (pp. 501–516). Elsevier. https://doi.org/10.1016/B978-0-12-813912-7.00020-X

PEGC (Pure Earth & Green Cross). (2016). World's worst pollution problems: the toxins beneath our feet. NY USA, Zurich Switzerland, 1–56. http://www.worstpolluted.org/2016-report.html

Persaud, D., Jaagumagi, R., & Hayton, A. (1993). Guidelines for the protection and management of aquatic sediment quality in Ontario.

Rai, P. K., Lee, S. S., Zhang, M., Tsang, Y. F., & Kim, K. H. (2019). Heavy metals in food crops: Health risks, fate, mechanisms, and management. *Environment International*, *125*, 365–385. https://doi.org/10.1016/j.envint.2019.01.067

Raini, J. A. (2009). Impact of land use changes on water resources and biodiversity of Lake Nakuru catchment basin, Kenya. *African Journal of Ecology*, *47*, 39–45. https://doi.org/10.1111/j.1365-2028.2008.01048.x

Reid, S. D. (2011). Molybdenum and chromium. In C. M. Wood, A. P. Farrell, & C. J. Brauner (Eds.), *Homeostasis and toxicology of essential metals*, *31* (pp. 375–415). Academic Press. https://doi.org/10.1016/S1546-5098(11)31008-4

Schagerl, M., Burian, A., Gruber-Dorninger, M., Oduor, S. O., & Kaggwa, M. N. (2015). Algal communities of Kenyan soda lakes with a special focus on Arthrospira fusiformis. *Fottea Olomouc*, *15*(2), 245–257. https://doi.org/10.5507/fot.2015.012

Talling, J. F., & Talling, I. B. (1965). The chemical composition of African lake waters. *Internationale Revue der Gesamten Hydrobiologie und Hydrographie*, *50*, 421–463.

Tenai, B. C., Mbaria, J. M., Muchemi, G. M., Jansen, R., Kotze, A., Naidoo, V., & Gitau, F. K. (2016). Assessment of heavy metals concentration in water, soil sediment and biological tissues of the lesser flamingos in four eastern rift valley lakes. *African Journal of Environmental Science and Technology*, *10*(6), 162–166.

Tibihika, P. D., Meimberg, H., & Curto, M. (2022). Understanding the translocation dynamics of Nile tilapia (*Oreochromis niloticus*) and its ecological consequences in East Africa. *African Zoology*, *57*(4), 171–179. https://doi.org/10.1080/15627020.2022.2154169

Turekian, K. K., & Wedepohl, K. H. (1961). Distribution of the elements in some major units of the earth's crust. *Geological Society of America Bulletin*, *72*(2), 175–192. https://doi.org/10.1130/0016-7606

USEPA. (2012). Mid-Atlantic Risk Assessment. United States Environmental Protection Agency. https://www.epa.gov/risk/human-health-risk-assessment

USEPA. (2017). Regional Screening Levels (RSLs) – User's Guide (November 2017). United States Environmental Protection Agency. https://www.epa.gov/risk/regional-screening-levels-rsls-users-guide-november-2017

Vareschi, E. (1982). The ecology of Lake Nakuru (Kenya). *Abiotic Factors and Primary Production Oecologia (Berl.)*, *55*(1), 81–101. https://doi.org/10.1007/BF00386722

WHO. (2003). *Cadmium in drinking-water. Background document for preparation of WHO guidelines for drinking-water quality*. World Health Organization (WHO/SDE/WSH/03.04/80).

WHO. (2010). *Exposure to arsenic: A major public health concern*. *Agriculture*, *5*. World Health Organization.

WHO. (2011). *Guidelines for drinking water quality* (4th ed.). World Health Organization.

Yabe, J., Ishizuka, M., & Umemura, T. (2010). Current levels of heavy metal pollution in Africa. *Journal of Veterinary Medical Science*, *72*(10), 1257–1263. https://doi.org/10.1292/jvms.10-0058

Yang, Y., Wei, L., Cui, L., Zhang, M., & Wang, J. (2017). Profiles and risk assessment of heavy metals in great Rift Lakes, Kenya. *CLEAN - Soil, Air, Water*, *45*(3), 1600825.

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