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Spatial Distribution and Potential Risks of Mercury in Surficial Sediments of the Kenyan Waters of Lake Victoria

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Abstract

Mercury is among the potentially harmful elements of concern globally, with known toxicity and potential for bio-magnification in aquatic food webs.In Lake Victoria, initial sediment core total Hg data has been provided, but THg distribution in Nyanza gulf are not well known, despite the available data from Napoleon gulf, Uganda, and its reported occurrences around gold mining areas. Surficial lake sediments were collected in 2012 and 2010 (from 26 and 24 sites respectively) from the Kenyan portion of Lake Victoria (East Africa) and the sedimentary characteristics and THg contents determined. The detectable THg concentrations had a spatial mean (±standard deviation) of 167±21ng/g dry weight. Surficial sediments contained high organic matter contents, which were positively correlated to THg. The sediments enrichment factors ranged from 0.4 to 33.8 showing anthropogenic effects although levels measured were similar to those found in other lakes. An assessment of the potential ecological effects for bottom dwelling organisms was made based on the mercury concentrations. There is need of continued awareness creation on improved waste management and treatment technologies, and the use of better techniques in Au mineral processing.

Keywords: Lake Victoria, Mercury concentration, Nyanza gulf, Sediment quality, Surficial sediments

Introduction

Mercury can follow a myriad of pathways through the environment but, with the exception of isolated cases of known point sources, the ultimate source of mercury to aquatic ecosystems is deposition from the atmosphere. Large uncertainties remain in global estimates of mercury emissions to the air, but on land it is largely retained in soils and vegetation, increasing the available pool for remobilization to adjacent aquatic ecosystem (UNEP, 2013).Mercury and methylmercury are contaminants of concern in fish and seafoods globally since they are the main source of exposure in humans (Huss *et al*., 2003). In East Africa, an environmental and health assessment in a small-scale gold mining area in Tanzania found that mercury levels were above the toxicological threshold limit only in amalgam burners (Appleton *et al*., 2005; O'Reilly *et al.,* 2010). Several investigators have reviewed and characterised bioaccumulation and biomagnification of mercury in Africa and several East African lakes (Campbell *et al.,* 2003a, 2003b; Kidd *et al.,* 2003; Black *et al.,* 2011; Poste *et al.,* 2014, 2015).

A review by Hanna *et al*. (2015) on mercury concentrations in freshwater fishes of Africa confirmed its bioaccumulation. However, mean mercury concentration exceeded the WHO/FAO recommended guidelines only at locations near artisanal and small-scale gold mining operations. Bioaccumulation of mercury has been noted in the food chain in the lake, with concentrations in some large Nile perch exceeding the WHO safety guidelines (Campbell *et al*., 2003a, 2004; Ogoyi *et al*., 2011; Machiwa 2004). The threat to commercial fish species is of great concern, but in most cases only a small number of fish species and biotic samples have been analysed. The large surface area of Lake Victoria is a potential route of mercury deposition although no estimates exist. Investigations into mercury concentrations in the lake ecosystem and inflowing

rivers are therefore necessary to understand the modifying factors or controls on mercury and its contributions from diverse sources.

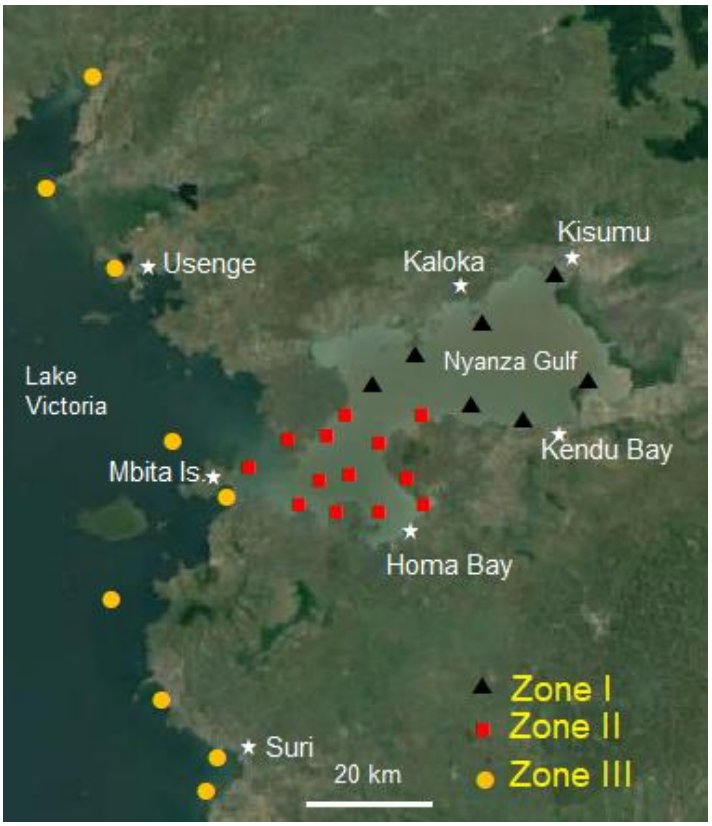

Figure 1. The Kenyan waters of Lake Victoria showing the location of the Nyanza Gulf and the sampling stations in the three main zones. Note the difference in colour of the semi-enclosed gulf and the main lake. (Image from Google Earth, 2018.)

Although the Nyanza (Winam) Gulf in the Kenyan sector of Lake Victoria (Figure 1) has a wide river drainage system, there are no detailed reports on mercury in its sediments. Several studies around gold-mining operations in the Kenyan portion of the Lake Victoria basin reported variable concentrations of heavy metals and mercury in biota, humans, mine waters, mine tailings and sediments of streams in the vicinity (Ogola *et al.*, 2002; Odum *et al.*, 2011a, 2011b, 2014; Ngure *et al.*, 2014). Mercury is used mainly for processing primary gold veins in quartz and supergene gold mineralization and some 70-80% of it is lost to the atmosphere during processing, and the remainder to tailings, soil, stream sediments and water (van Straaten, 2000). Mercury is used by small-scale gold miners in more 50 developing countries where the accompanied releases affect human health and the environment (Veiga *et al.*, 2006). Kenya. Campbell *et al.* (2003a) sampled at two sites in the Nyanza Gulf, but there are no more detailed investigations of mercury in the surficial sediments of the gulf.

Lake Victoria is a wide depositional basin and its sediments provide habitat for benthic invertebrates and fish but they are a potential secondary source of mercury, and hence the need for adequate and continuous data on its potential sources and distribution. This paper provides more comprehensive data on the distribution and concentrations of mercury in the Nyanza gulf and adjacent parts of Lake Victoria.

Methods

Study area

Lake Victoria is the second largest freshwater lake and the largest in Africa with an area of about 68,800 km^2, mean and maximum depths of 40m and 80m respectively, and a volume of about 2,760 km^3. Direct rainfall provides about 80% of the lake's water input with the balance coming from rivers. This is balanced by evaporation which accounts for a similar proportion of its losses with remainder being discharges down the Nile. The remaining inputs is from rivers and the flushing time (volume/outflow) is from 80-120 years (Sewagudde, 2009).

The lake's bottom is mainly covered by a thick layer of organic mud, but with patches of hard substrate, sand and shingle or rock (Scholz *et al.*, 1990). The lake became eutrophic in the mid-1980s with extensive blooms of blue-green algae contributing to an increase in the deposition of organic matter in the sediments and subsequent deoxygenation of deeper waters (Hecky *et al*, 2010) although rapid warming of deeper waters in the lake between 1999-2001 and 2005-2009 may have reduced the thermal gradient and weakened stratification and the extent and severity of deoxygenation (Sitoki *et al.*, 2010). The water hyacinth outbreak, which began in 1989 and peaked in 1998-99 would also have deposited organic matter but as this weed has been significantly reduced through biological control its contribution will have diminished (Albright *et al*., 2004; Wilson *et al*., 2007).

The Nyanza Gulf is a shallow, semi-enclosed arm of Lake Victoria that extends into the Kenyan portion of the lake. Its catchment area is dissected by several rivers and tributaries, the principal ones being the Nyando, Nyamasaria, Sondu-Miriu and Awach. Rivers

Yala, Sio, Nzoia, and Kuja are major inflowing rivers into the main lake. The river mouths, shallow inner bays and island shores are important habitats for fish and inshore zone (< 5 m deep) is the most important area for artisanal fisheries (Balirwa *et al*., 2005).

Sampling

A monitoring survey was carried out in June 2012 and attempted, as far as possible, to sample the same stations used during the 2010 survey; the locations were identified by their GPS coordinates. Some physico-chemical variables of water overlying the bottom sediments were determined *in situ* using a CTD-90 M sensor (Sea & Sun Technology). The sampling stations were setup in the three major zones, as follows:

Zone I: The inner shallow eastern portion of the Nyanza Gulf influenced by the rivers Kibos-Nyamasaria, Nyando, Awach and Sondu-miriu, with an average water depth of about 5m (12 stations). The major urban area of Kisumu borders this zone.

Zone II: The deeper waters of the gulf zone connected to open waters. The River Oluch enters the lake near Homa Bay, the largest urban centre in this zone.

Zone III: Open lake, south and north. Open lake waters with shallow nearshore margins, exposed to heavy wind and wave action. Influenced by the rivers Kuja in the south and rivers Sio, Nzoia and Yala in the north. Sampled lake sites ranged from shallow areas (1.2 m depth) to relatively deep gulf sites (up to 14m depth)., whereas depth ranged from 3m to 54m in the main lake sites.

Bottom sediments were collected with a pre-cleaned Ponar grab sampler. The innermost portions of sediments were used for gravimetric determinations and trace metal chemical analysis, to avoid parts in contact with the grab sampler. The field samples were kept frozen in pre-cleaned high-density polythene bags in the field, prior to initial sample preparation in the laboratory. The sediments were dried in oven at temperatures below 50 ºC (to avoid mercury losses), crushed to powdered form and sieved. The sediments were characterized by determination of the percentage water, carbonate and organic matter contents. The water content was determined by oven-drying about 5.0g of the wet sediment at 105 ºC for 6 hours and to constant weight. About 1.0g of the dry sediment was used to determine the carbonate and organic matter contents according to Hakanson and Johasson (1983).

The dry sediment powder (dried below 50 ºC) was submitted to the National Kenya Plant Health Inspectorate services (KEPHIS) laboratories, Nairobi, for Hg analysis using the standard Cold Vapour Atomic Absorption (CVAA spectrometry) techniques, applying clean techniques to minimize potential contamination. Samples were analysed and treated according to KEPHIS QA/QC procedures. All reagents used were of analytical grade to check for possible contamination, and blank digests were carried through the same procedures. Results of total mercury were reported on dry weight basis.

Results

Water quality in the study area generally exhibited a trend from the shallow water in the semi-enclosed gulf (Zone I) to the open waters of the lake (Zone III). Thus, pH, conductivity, alkalinity and hardness all decreased from Zone I to Zone III while transparency (Secchi disc) and dissolved oxygen increased (Table 1). There was relatively little variation in water temperature between the zones and no evidence of thermal stratification at the time of sampling. There was also little variation with depth in any other variables, apart from conductivity which was higher at the bottom in all zones and dissolved oxygen, which was reduced in the bottom waters of Zone III.

Table 1. Some physico-chemical characteristics of the water (mean ± SD) in the three zones.

		Zone I	**Zone II**	**Zone III**
	Mean depth (m)	**3.8 ± 2.3**	**7.2 ± 5.1**	**17.8 ± 19.0**
Temperature (˚C)	Surface	24.73 ± 0.65	24.91 ± 0.56	25.50 ± 0.37
	Mid-water	24.33 ± 0.69	24.51 ± 0.29	24.92 ± 0.34
	Bottom	24.23 ± 0.65	24.46 ± 0.28	24.58 ± 0.60
pH	Surface	8.04 ± 0.25	7.84 ± 0.19	7.91 ± 0.23
	Mid-water	8.02 ± 0.27	7.82 ± 0.19	7.83 ± 0.20
	Bottom	7.95 ± 0.30	7.71 ± 0.13	7.70 ± 0.23
Conductivity (µS cm^{-1})	Surface	154 ± 18	147 ± 11	111 ± 4
	Mid-water	152 ± 24	147 ± 11	109 ± 4

	Bottom	172 ± 28	166 ± 29	118 ± 26
Dissolved oxygen (mg l^{-1})	Surface	7.51 ± 1.82	7.18 ± 0.87	8.45 ± 1.21
	Mid-water	7.13 ± 1.42	6.95 ± 0.87	8.60 ± 1.75
	Bottom	6.81 ± 1.29	6.76 ± 0.85	7.27 ± 1.89
Secchi depth (m)	Surface	0.28 ± 0.06	0.42 ± 0.27	1.8 ± 0.83
Alkalinity (mg l^{-1})	Surface	101 ± 52	53 ± 8	39 ± 21
Hardness (mg l^{-1})	Surface	49 ± 14	49 ± 15	29 ± 4

In 2012, thepercentage of calcium carbonate and water in the sediments was significantly higher (for both; ANOVA, $p<0.05$)in the gulf (Zones I and II) than in the open lake (Zone III)but there was no difference in the percentage of organic carbon between the zones. The mercury concentrations varied widely but were not significantly different (Table 2). The water content of the sediments was significantly different between the three zones (ANOVA,$p<0.05$) and between the sampling water depth in the main lake (ANOVA,$p<0.05$) only. The calculated sediment bulk density ranged from 0.0218 to 0.0303 gcm^{-3} in the gulf and 0.0205gcm^{-3} to 0.0875 gcm^{-3}.

Table 2.Some characteristics (mean±SD) of surface sediments in 2010 and 2012.(Values in brackets indicate the number of samples; - = not determined).

		Water (%)	**Organic carbon (%)**	**Calcium carbonate (%)**	**Total mercury (ngg^{-}1d.w)**
2012	Zone I	86.19 ± 3.57(21)	10.64 ± 3.75(26)	2.30 ± 1.54(18)	200 ± 158(14)
	Zone II	86.34 ± 3.82(25)	9.93 ± 2.15(38)	2.70 ± 1.95(24)	108 ± 50(22)
	Zone III	72.43 ± 20.0(24)	9.80 ± 4.64 (25)	1.56 ± 0.75(16)	208 ± 212(16)
2010	Zone I	-	10.68 ± 3.31 (8)	-	610 ± 735(7)
	Zone II	-	14.97 ± 2.65(7)	-	131 ± 184(8)
	Zone III	-	7.21 ± 4.37(9)	-	83 ± 47(7)

The concentrations of total mercury were more variable in 2010 compared to 2012 (Table 2). Mercury was detected in all samples in 2012 survey where values ranged from values ranged from 46-720ngg^{-1}(overall mean = 167±152 ngg^{-1}, n = 52) but in 2010 mercury was not detected at 62% of the sampling sites. Only a few sites (n=9) recorded measurable total mercury concentrations, which ranged from 21.3-1130.1 ngg^{-1} dry weight. Apart from the single highest value of total mercury recorded in 2010 survey at site LS_6 (Zone I), all the other detected mercury concentrations in the 2010 survey, were within the range of values recorded in 2012.

In 2012, total mercury concentrations ranged from 86-176 ng g^{-1}at sites in the gulf and 46-302 ng g^{-1} at sites in the main lake. The highest concentration (302 ng g^{-1}) was recorded at site LS_23, the most southerly site in the main lake. In 2010, concentrations at sites off river mouths in the gulf reported concentrations ranging from 'not detected' to 90.3 ng g^{-1} while those the main lake off river mouth sites ranged from 'not detected' to 139 ng g^{-1} dry weight. These concentrations are lower than those found in other lake sites. At urban-influenced sites total mercury ranged from 54 to 218 ng g^{-1}, with mean values ranging from 64 ± 14 to 211 ± 10 ng g^{-1}. The single highest concentration recorded in the 2012 survey was at the deepest sampled site located in the main lake.

When sites are grouped according to zones and water depth (Table 3), there were no significant differences in the concentrations of total mercury. However, in the two main lake zones (northern and southern) the concentrations of total mercury were found to be significantly different ($p < 0.05$). The relationship between total mercury and organic matter (Figure 2) was highly significant ($p < 0.001$) but this should be treated with caution. If the five highest values (> 500 ng g^{-1}) are removed, the correlation is not significant (R^2 =

0.0406). This suggests that these values may be unusually high outliers. There were no correlations between mercury and calcium carbonate or water content in the sediments.

Table 3.The concentrations of total mercury (ngg^{-1}d.w.) and some sediment characteristics (mean ± SD) of surface sediments according to water depth (m) in 2010 and 2012 (nd = not detected; numbers in brackets indicate the number of samples; - = not determined).

		2010		2012	
Variable	**Depth (m)**	**Gulf**	**Main lake**	**Gulf**	**Main lake**
Total mercury (ng g^{-1})	< 5	414±621 (10)	80±29 (3)	115±53 (20)	94±61 (6)
	5-10	186±223 (4)	86±75 (4)	124±30 (10)	187±132 (4)
	> 10	nd (1)	nd (2)	159±104 (6)	337±292 (6)
Organic carbon (%)	< 5	10.5±2.8 (12)	5.6±4.1 (3)	10.4±3.1 (20)	6.8±4.7 (6)
	5-10	12.9±0.4 (2)	5.6±3.3 (4)	9.7±1.5 (10)	7.8±1.6 (4)
	> 10	15.8 (1)	12.9±1.9 (2)	10.1±1.0 (6)	13.7±2.9 (6)
Calcium carbonate (%)	< 5	-	-	2.2±1.2 (20)	1.1±0.7 (6)
	5-10	-	-	4.0±2.6 (10)	1.9±1.0 (4)
	> 10	-	-	1.6±0.2 (6)	1.8±0.4 (6)
Water (%)	< 5	-	-	86.2 ± 3.7 (26)	57.7 ± 23.9 (9)
	5-10	-	-	85.8 ± 3.7 (14)	70.1 ± 6.2 (6)
	> 10	-	-	88.7 ± 3.0 (6)	88.7 ± 3.9 (9)

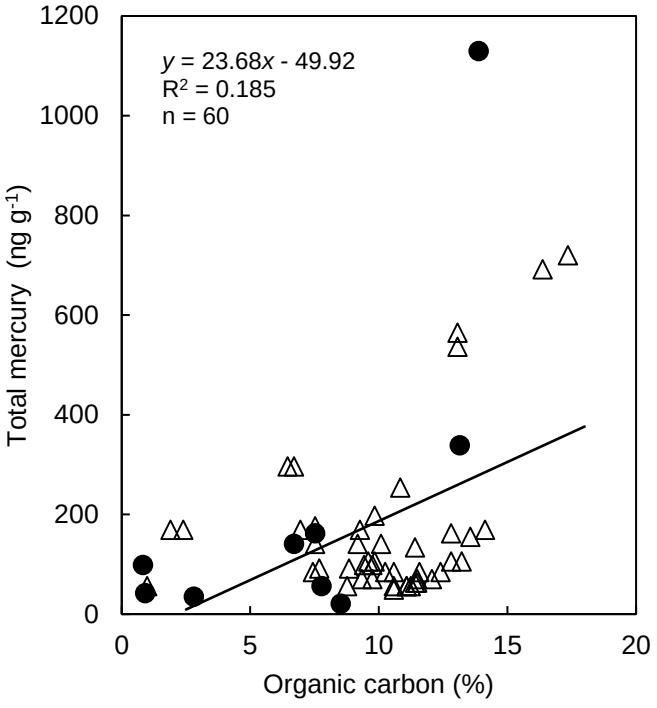

Figure 2. The relationship between total mercury concentrations (ngg^{-1} d.w.) and sediment organic carbon (%) in thesurveys of 2010 (●) and 2012 (△).

The concentrations of total mercury in the 2010 survey were mostly below the detection level andtherefore nostatistical evaluation was made. There was no significant difference in the total mercury concentrations in the sediments from gulf and open lake sites, or in relation to water depth, which could be due to the extent of contribution from different sources in a non-depositional basin (shallow narrow basin with well oxygenated gulf water study sites, with possible sediment re-suspension) and a deeper depositional basin (larger surface area of deep open lake offshore sites).

Discussion

Mercury in aquatic ecosystems is of concern because it can bioaccumulate in food chains in its toxic form, methyl-mercury, and understanding its concentration and distribution in Lake Victoria is important because of the lake's importance as a source of water and fish.

The concentrations of mercury in the sediments of the Nyanza Gulf and adjacent lake are relatively low and similar to most of those previously reported from the lake (Table 4). The values given by Ogoyi *et al*. (2011), however, seem to be too low and should probably be ignored. There seems to have been little change since the earliest values reported from 1995 but data from sediment cores indicate that mercury concentrations changed rapidly, beginning in the 1960s. Mercury concentrations in a sediment core from Itome, Uganda (a nearshore site) increased from about 120 to about 200 ngg^{-1}d.w.between 1900 and 1962(Ramlal *et al*., 2003). It then increased to about 300 ngg^{-1} around

1980 before falling back to ca. 200 ngg^{-1} in the 1990s. A similar pattern was noted in a second, deep-water core from the middle of the lake (V96-5MC) where the total mercury concentration was around 120 ngg^{-1} from 1900 to the late 1950s, after which it increased. Similar surface enrichments in both the gulf and open lake surficial sediments were reported in this study, indicating the increased influence of human activities on metal contents. In general, soils around the lake basin reflect background concentrations although regionally data are still very scarce.

In the southern Mwanza Gulf there were no significant difference ($p>0.05$) in mean mercury concentrations (overall mean of 1000 ngg^{-1} dry wt., n = 93) and sediment texture with increasing distance from the shoreline sediments (200 ngg^{-1}at 25m) to offshore (100ngg^{-1}at 2000m), but much higher concentrations were associated with river mouth areas(Kishe and Machiwa, 2003). This area of southern Lake Victoria is affected by gold mining in the hinterland as well as by activities in Mwanza city.

Table 4. Estimates of mercury in water and surface sediments in Lake Victoria, 1995-2012. All values are means unless shown as ranges. Ke = Kenya, Tz = Tanzania and Ug = Uganda. Sources; (1) Ramlal *et a*l. (2003), (2) Campbell *et al*. (2003a), (3) Kishe and Machiwa (2003), (4) Ogoyi *et al*. (2011), (5) Poste *et al*. (2015) and (6) this study.

Location	Water ($ng\ L^{-1}$)	Sediment ($ng\ g^{-1}$)	Source
Bugaia (Ug), 1995	3-15		1
Offshore core V96-5MC, 1995		*292	2
Itome Bay Core (Ug), 1996		180	2
Speke Gulf (Tz), 1996	<200	< 10	2
Emin Pasha Gulf (Tz), 1996		30	2
Napoleon Gulf (Ug), 1998-99	1.7-15.5		2
Nyanza Gulf (Ke), 1988-89	2.9-4.5		2
Mwanza Gulf (Tz), 200		**200	3
Nyanza Gulf, 2008	0	1-13	4
Mwanza Gulf, 2008	nd-1	3-9	4
Napoleon Gulf, 2008-09	0.45		5
Murchison Bay (Ug), 2008-09	1.30		5
Nyanza Gulf, 2010		323	6
Open lake (Ke), 2010		83	6
Nyanza Gulf, 2012		149	6
Open lake, 2012		208	6

Note:

*Values from mines, rivers and other localities not included.

**Values don not include a value of 2800 ng g^{-1} which was recorded from a site near an urban area.

The concentrations of total mercury in the water are relatively low (Table 4) while the concentration of methyl mercury in Lake Victoria was also low, ranging from 0.2-1.0 ngL^{-1}(Campbell *et al*., 2003a). The drinking water guidelines (WHO, 1990) allow a concentration of 1.0 µg L^{-1} for mercury, and thus the concentrations of mercury in Lake Victoria water is well below that value. The low concentrations of mercury in the lake's water are also reflected in the low and undetectable mercury concentrations in the sediments.

The association of mercury with organic carbon in the sediments supports the high sediment enrichment factors (SEF's were above value of 1, but less than 40, which is indicative of enrichments) found for total mercury, which implies that the influence of anthropogenic factors is of importance to the total Hg concentrations. SEF's show no clear trends among the sites, indicating that inputs of Hg could be emanating from varied sources and other complex processes of deposition of organically bound Hg and dilution within the shallower lake zones. Such values also need to be used with caution as there are no well-established mercury background values in lake sediments for the Kenyan portion of the lake. There are presently no data on atmospheric mercury to support the possibility of increased mercury loading from various sources, such as fossil fuels, in the lake basin. There is also very limited information on other species of mercury in the lake, which is needed to understand the mercury pool in sediments.

Various evaluation criteria have been developed to evaluate the potential ecological risks of mercury in sediments. These include two consensus-based sediment quality guidelines, the threshold effect concentration (TEC) and probable effect concentration (PEC) values (Macdonald *et al.*, 2000). The 95% confidence limit of the overall mean for the bulk sediment mercury (208 ngg^{-1}) in Lake Victoria exceeded the upper level of no effect (TEC = 180 ngg^{-1}) but were still below the PEC values (1060 ngg^{-1}) (Table 5). Similarly, the interim sediment quality guideline value (ISQG) for freshwater sediments

(CCME, 1999) were exceeded by the 95% confidence limit for the bulk sediment overall mean of mercury. Only 25% and 39% of the samples contained total mercury concentrations above the TEC and ISQG values. The trigger value for mercury (ISQG-low = 150 ngg^{-1}) above which further ecosystem specific investigation is recommended for the Australian and New Zealand sediments quality guidelines (Cox and Preda, 2005) was exceeded in Lake Victoria. Nevertheless, this approach used only allows for decisions for the need of specific assessments, as the toxicity to sediment dwelling organisms will be determined by the amounts of the elements (bio-available) available for uptake.

Table 5. The mean concentrations of total mercury (ng g^{-1}d.w.) in sediments from the three zones of Lake Victoria, in relation to three quality guidelines. The symbol * denotes a value that exceeds both the ISQG and TEC values, while ‡ denotes a value that exceeds ISQG only. Values in parenthesis are number of samples.

Standard	**ISQG-low**	**150**
	TEC	**180**
	PEC	**1060**
L. Victoria data (this study	Zone I	291* (16)
	Zone II	144 (22)
	Zone III	321* (16)
	Gulf < 5m	225* (20)
	6-10 m	146 (10)
	>10 m	268* (6)
	Lake < 5m	158‡ (6)
	6-10 m	397* (4)
	>10 m	643* (6)

Mercury contamination in Lake Victoria is of concern since detailed data for the different components are not available, as noted in some reviews (Campbell *et al.*, 2003b; Hanna *et al.*, 2015; Poste *et al.*, 2015). The sediments in the extensive shallow areas (<5m) of the Nyanza Gulf have the potential to influence chemical concentrations and element remobilisation through sediment resuspension and this potential source of mercury needs to investigated, along with atmospheric sources derived from biomass burning. Biomass burning (Friedli *et al*., 2009; St. Louis *et al.*, 2001; Roberts and Wooster, 2007) and small-scale gold mining activities (Telmer and Veiga, 2009) are among the processes that contribute to the release of mercury and its transport over large areas. The quantity of total gaseous mercury detected in a smoke plume at Cape Point (34˚S,18˚E), South Africa in mid-January 2000 suggest that mercury emissions from biomass burning might be substantially larger than assumed and might constitute one of the major sources of atmospheric mercury (Brunke *et al*., 2001). Gaseous mercury gets trapped on vegetation through wet and dry deposition and can be incorporated into plant tissue or photo-chemically reduced to gaseous elemental mercury and released, or it can be washed off as through fall. The contribution of xylem sap to mercury in plants is minor (Bishop *et al*., 1998) except for plants in soils with high mercury content, whether contaminated or naturally enriched.

Lake Victoria lies within the tropical zone with extensive tropical forests, savanna grasslands, agricultural fields and scattered artisanal mining activities around the basin. Although there are no flux data from these sources, they still form another important pathway for the entry of mercury into the lake, which needs further investigation. Riverine sources also need to be investigated along with atmospheric inputs, bioaccumulation and biomagnifications in both Lake Victoria and other lakes in the region. This would generate a greater understanding of mercury pools and their transformation into the more toxic methylated form. It would also support and improve environmental impact assessments creating community awareness of the impacts of mining in the Lake Victoria basin. It would also contribute to a reduction in the impacts of uncontrolled gold-mining and abandoned mining areas, which contribute to catchment degradation and lake metal enrichment.

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