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A REVIEW OF MERCURY IN LAKE VICTORIA, EAST AFRICA: IMPLICATIONS FOR HUMAN AND ECOSYSTEM HEALTH

Linda M. Campbell, D. G. Dixon, R. E. Hecky

Department of Biology, University of Waterloo, Waterloo, Ontario, Canada

Lake Victoria, East Africa, has been the site of many recent studies measuring mercury (Hg) concentrations in water, fish, sediment, soil, and humans. Most of these studies were motivated by concerns about Hg contamination from processing of gold ore on the southern shores. Total Hg (THg) concentrations in fish were usually below permissible World Health Organization (WHO) concentrations and international marketing limits and do not threaten the lucrative export industry. Nile perch 3–10 kg and most >10 kg had THg concentrations above the WHO threshold concentrations for at-risk groups (200 ng/g). Elevated THg concentrations in large Nile perch are not of major concern because Nile perch are rarely consumed by the people living on Lake Victoria and very large Nile perch are becoming increasingly rare in catches. Water THg concentrations were below Canadian drinking water guidelines but were elevated relative to those in the northern Great Lakes. Sediment and soil THg concentrations were within international guidelines and are comparable to those in northern latitudes but are lower than those in the Amazon basin. Biomass burnings and soil erosion are estimated to be the major sources of THg for the lake and probably constitute a larger source of THg than gold mining in Tanzania. THg concentrations in urine and hair from human volunteers indicate that while gold miners and frequent skin-bleaching cream users are at risk of inorganic mercury poisoning, the rest of the population, including fishermen, is not. Human exposure assessments demonstrated that fish consumption and soil geophagy constitute major sources of THg for humans, but the total estimated daily intake of THg was below the Health Canada tolerable daily intake (TDI) limits. The use of beauty creams containing high inorganic Hg concentrations, however, caused the estimated THg exposure to exceed the TDI. The high THg content in the hair of regular cream users supports this assessment. The nutritional benefits of fish and soil geophagy outweigh the risk of THg poisoning. Still, due to the importance of those natural items as a THg source to humans, as well as the changing nature of Lake Victoria, regular monitoring and risk assessments need to be carried out in the Lake Victoria catchment.

In Africa, mercury (Hg) pollution of aquatic ecosystems can potentially be devastating, because there is both high dependence on untreated water and relatively few regulatory controls for monitoring and mitigating aquatic contaminants. Human exposure assessment and environmental monitoring are not widespread practices, since limited resources force African governments

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Address correspondence to Dr. Linda Campbell, Canada Centre for Inland Waters, PO Box 5050, 867 Lakeshore Road, Burlington, Ontario L7R 4A6, Canada. E-mail: lmcampbe @uwaterloo.ca

to focus on immediate health concerns such as infant mortality, malnutrition, and infectious diseases. In his 1992 review of metal pollution in Africa, Nriagu states that:

> *Environmental toxins induce chronic and degenerative health effects which are difficult to link directly to exposures and the symptoms are often indistinguishable from those of the communicable diseases. The management of the hazards associated with toxic contaminants in the African environment thus entails a different and difficult type of health care and has so far been accorded benign neglect. (p. 2)*

This holds true in Africa 10 years later, particularly for Hg. The two major reviews of African metal pollution published in the early 1990s (Nriagu, 1992; Biney et al., 1994) list only a few studies examining Hg in African aquatic environments, most of them dating pre-1990s. Since then there has been resurgence in Hg research in Africa, with most published studies focusing on Lake Victoria. The fisheries of Lake Victoria, the largest tropical lake in the world by area (68,800 km^2), are economically important and rely on fish exports to the European Union (Republic of Uganda, 1999). Fish also provide an essential source of protein for people living around the lake. Dependence on the fisheries and the need for a healthy environment in the three countries sharing the lake (Tanzania, Uganda, and Kenya) has stimulated a series of studies focusing on Hg in the region.

Hg is a particular concern in aquatic environments and fish because Hg compounds can be microbially transformed into methylmercury (MeHg) in water and sediments (Sweet & Zelikoff, 2001). MeHg can biomagnify approximately 10^6-fold through the food web, resulting in high total mercury (THg) concentrations in piscivorous fish relative to water, even in areas remote from industrial sources (Fitzgerald et al., 1998). Many of the environmental Hg studies in developing countries have been prompted by concerns about gold (Au) ore processing practices in developing countries where Au-Hg amalgamation is common (Reuther & Malm, 1997; Artaxo et al., 2000; Counter et al., 2002). Finely ground Au ore is hand mixed with liquid Hg, allowing the Au to solublize in the Hg. The Au is recovered by burning the Au-Hg amalgam in a cloth ("sponge") over a fire, which releases the Hg to the atmosphere. It has been estimated that about 1.46 g Hg is emitted for every gram of Au recovered (van Straaten, 2000a). These practices are widespread in the gold fields of Tanzania on the southern shores of Lake Victoria (Ikingura & Akagi, 1996; van Straaten, 2000a).

Other potential major sources of Hg to Lake Victoria include biomass burnings. Plants assimilate Hg from the soil and when burned release stored Hg to the atmosphere (Freidli et al., 2001). The majority of precipitation to Lake Victoria is derived from the lake catchment (Bootsma & Hecky, 1993), which frequently experiences agricultural burning. Globally, 50% of the fires seen in satellite observations are located in sub-Saharan Africa (Dwyer et al., 2000), indicating that biomass burnings are a highly significant potential source of THg to African lakes (Campbell, 2001). Soil erosion is another potentially

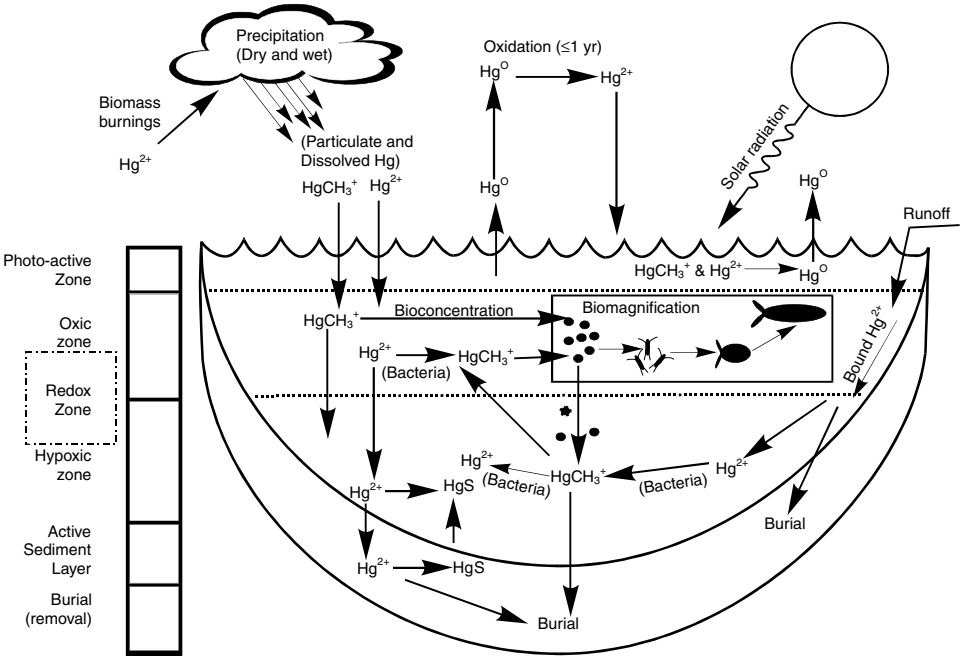

FIGURE 1. Theoretical cycling of MeHg ($HgCH_3^+$ in the figure) in lakes. The figure is based on diagrams in Sellers et al. (1996), Amyot et al. (1994), and Morel et al. (1998).

important Hg source to Lake Victoria, as sequestered Hg in soil oxyhydroxide particles can be released rapidly upon reduction in water (Roulet et al., 1998).

Hg biogeochemistry in tropical freshwater lakes is a little-studied topic (Bowles et al., 2001; Campbell, Hecky, Nyaundi et al., 2003; Kidd et al., 2003). Most of the tropical and subtropical aquatic Hg studies have focused on river systems in the Amazon Basin and globally unique wetland terrain in the Florida Everglades (Gilmour et al., 1998; Roulet et al., 1998). When it comes to monitoring Hg in lakes, MeHg compounds (chemical formula $HgCH_3^+$) are of primary concern because MeHg is highly bioaccumulative (Morel et al., 1998). Other Hg compounds (Hg^{2+}, Hg) do not bioaccumulate easily. THg represents the sum of MeHg, Hg^{2+}, Hg, and other Hg compounds that are measured in an environmental sample and is the most commonly measured component because of the high cost of compound-specific Hg analysis, even though methylation rates and the amount of MeHg are the primary concern. Figure 1 shows a simplified diagram of the aquatic cycling of Hg compiled from several sources (Amyot et al., 1994; Sellers et al., 1996; Morel et al., 1998). Atmospheric and terrestrial sources of THg will both enter the lake. In this hypothetical lake there are five zones (layers), three in the water column and two in the sediment; Hg chemistry will be somewhat different in each layer. The first layer, the photoactive zone, is the top 2 m of the lake where solar radiation easily penetrates the water surface

(Amyot et al., 1994; Sellers et al., 1996). Solar radiation is known to rapidly photodegrade MeHg and Hg^{2+} into Hg^0, which is then lost from the lake by volatilization (Amyot et al., 1994; Nriagu, 1994; Sellers et al., 1996). This can be a significant loss for Lake Victoria with its huge surface area and exposure to intense tropical solar radiation (Campbell, 2001). The oxic zone is the layer of well-oxygenated water below the photoactive zone and is where most fish, invertebrates, and algae reside. MeHg and Hg^{2+} that are derived from atmospheric sources (both adsorbed on particulates and dissolved in rain) and from soil erosion and runoff can undergo oxidizing reactions in this zone. MeHg is rapidly *bioconcentrated* from water by algae, while Hg^{2+} may be derived by bacteria from MeHg. *Biomagnification*, the process of food-web transfer, continues when invertebrates consume the algae and, in turn, are eaten by fish and thus up the food chain. With each successive trophic level, THg concentration increases (Cabana et al., 1994). Dead algae carrying MeHg may sink into the hypoxic zone, the water layer with low oxygen concentrations. Hg^{2+} and MeHg compounds entering the hypoxic zone are easily reduced and bind with reduced sulfide (HgS), which is insoluble and settles into the lake sediments (Morel et al., 1998). Sulfate-reducing bacteria that methylate Hg^{2+} compounds are more frequently found in hypoxic/anoxic conditions and may result in higher MeHg production (Gilmour & Riedel, 1995; Gilmour et al., 1998). The gradient between the oxic and hypoxic zones is the redox transition zone where Hg chemistry changes from oxidizing to reducing conditions. Soil oxyhydroxide particles with bound Hg^{2+} from runoff and erosion go through reduction shifts and release more Hg in the hypoxic zone (Meili, 1997). The sudden shifts at the redox transition zone result in a "peak" in Hg^{2+} concentrations just below the oxic zone boundary (Regnell et al., 2001). Once Hg compounds pass to the active sediment layer, they enter into another redox flux at the sediment-water interface if oxygen is available (Morel et al., 1998). The redox flux continues until enough sediment settles to bury the Hg compounds in deep sediments, removing the Hg from active cycling in the lake (Lockhart et al., 2000).

Tanzania, because of its large Lake Victoria goldfields, was the first country to initiate ongoing Hg research on the lake. In Kenya and Uganda, recent questions expressed in the general media (Byarugaba, 2001) and by scientists have raised concerns about the actual Hg concentrations in the fish and water and whether those concentrations represent a real threat to the lake and the people dependent on the lake. In response to those concerns, recent studies on Hg in and around Lake Victoria were compiled, and a preliminary assessment of human and environmental health risks was undertaken.

METHODOLOGY

Laboratory and Field Protocols

It is important to keep in mind that all the studies compiled used different laboratories, quality control/quality assurance (QC/QA) protocols, and analytical

methods. The most common method for analyzing THg in fish and sediment was to extract the THg by hot digestion in strong acids (nitric, nitric-sulfuric, or some combination of other strong acids) and then analyze the extracts by cold-vapor atomic absorption spectrophotometry (CV-AAS; Campbell et al., unpublished; Harada et al., 1999), atomic fluorescence spectroscopy (AFS; Campbell, Hecky, Nyaundi et al., 2003), or inductively coupled plasma atomic emission spectrometry (ICP-AES; van Straaten, 2000a). Water samples are easily contaminated and were normally sampled in the field using "clean hands–dirty hands" methods (Bloom & Crecelius, 1983). Water samples were usually collected in precleaned Teflon containers, but one study used "sterilized" polypropylene vials (van Straaten, 2000a). Water samples were preserved with a small amount of ultrapure strong acid and stored at low (0 to −5 °C) temperatures. Most water samples were unfiltered, except for those collected from Isanga River sites near Mwanza Gulf (van Straaten, 2000a). Water samples were analyzed by inductively coupled plasma mass spectrometry (ICP-MS; van Straaten, 2000a), CV-AAS (Ramlal et al., 2002), or $SnCl_2$ reduction with fluorescence detection (Campbell, Hecky, Nyaundi et al., 2003). Any attempt to statistically infer trends and patterns in THg distribution across Lake Victoria using the compiled data would be confounded by unknown variations in interlaboratory analytical differences, temporal patterns, and sampling protocols. Therefore, the THg concentrations and distribution were quantitatively compared among studies and the discussion of THg patterns in Lake Victoria is based on conclusions drawn from all studies.

Comparison of Reviewed Data

For consistent comparisons, published THg concentrations were converted, if necessary, to standard units. THg concentrations in fish were expressed as nanograms per gram (ng/g) wet weight (ww) to be consistent with international regulatory limits. Dry weight (dw) THg concentrations in fish were converted to wet weight values using the factor 0.31 (Ramlal et al., 2003). Sediment THg concentrations were expressed as nanograms per gram dry weight (ng/g dw), while water THg concentrations were expressed as nanograms per liter (ng/L). Only studies published after 1990 that specifically used ultratrace sampling and accepted laboratory methods were considered. Studies prior to the late 1980s rarely used ultratrace methods, and the subsequent published values are frequently inaccurate (Fitzgerald et al., 1998). A map (Figure 2) shows the locations of the different study sites included. The assessment of human exposure to THg around Lake Victoria was based on the data presented here and on the protocols outlined by Health Canada for exposure calculations (Health Canada, 1995).

The data are compiled in a series of tables, with Table 1 listing the references compiled for this review. Table 2 details the THg concentrations in five common Lake Victoria fish species. Table 3 lists THg concentrations in water samples from across Lake Victoria, while Table 4 itemizes sediment and soil THg concentrations. Table 5 compiles a survey of published (≥1990) THg concentrations in environmental and human samples from other regions across

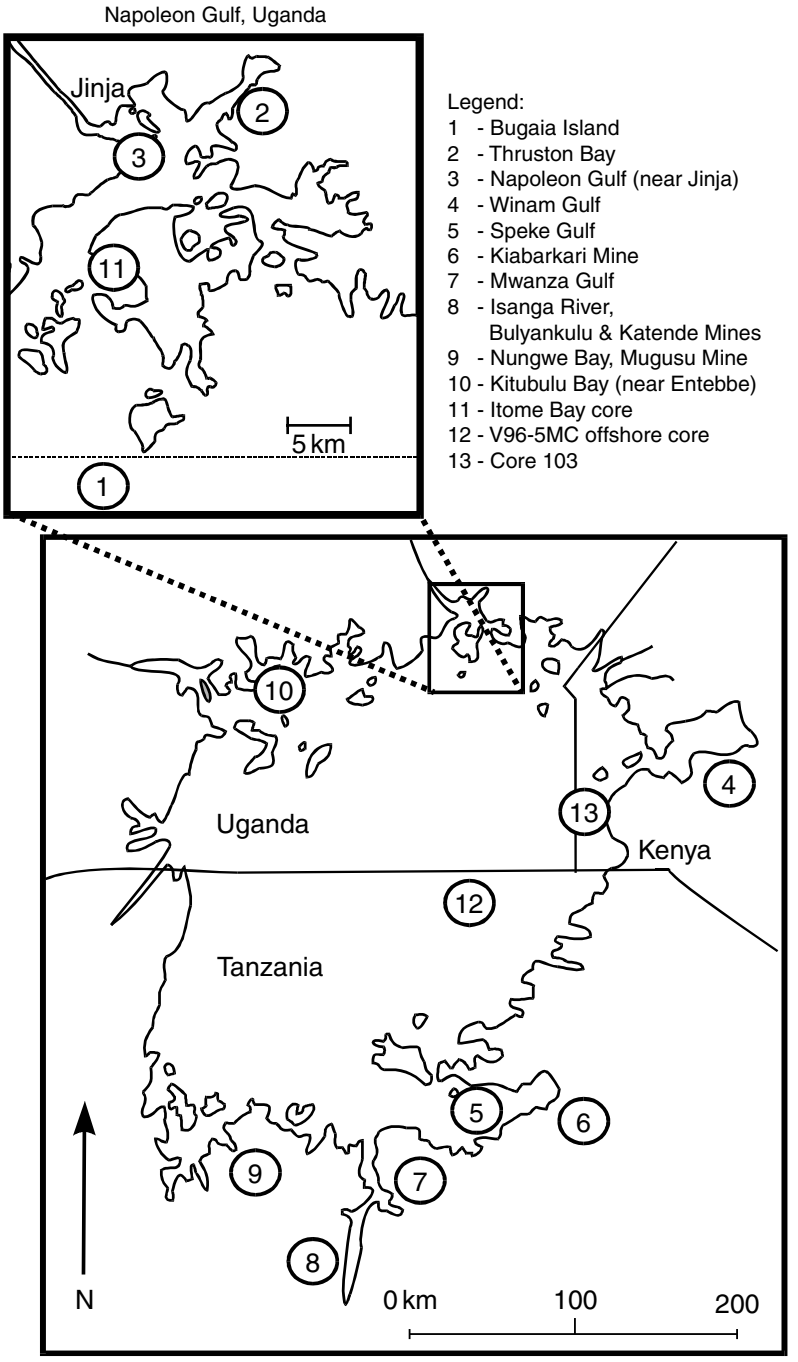

FIGURE 2. Map of Lake Victoria with the reviewed sampling sites indicated.

TABLE 1. Key to Citations for Tables 2 to 6

Citation code	Reference
1	Calamari et al., 1995
2	Campbell unpublished
3	Campbell, Hecky, Nyaundi et al., 2003
4	DHV Consultants BV et al., 1998
5	Harada et al., 1999
6	Harada et al., 2001
7	Ikingura and Akagi, 1996
8	Japanese NGO Mission for Lake Victoria Environmental Monitor '96, 1997
9	Kahatano and Mnali, 1997
10	Kahatano et al., 1997
11	Migiro, 1996
12	Ramlal et al., 2003
13	van Straaten, 2000a
14	van Straaten, 2000b
15	Biney and Beeko, 1991
16	Bonzongo et al., 1996
17	Brunke et al., 2001
18	El-Demerdash and Elagamy, 1999
19	Khassouani et al., 2001
20	Kidd et al., 1999
21	Kidd et al., 2003
22	McNab et al., 1997
23	Mhlanga, 2000
24	Oosthuizen and Ehrlich, 2001
25	Osfor et al., 1998
26	Sindayigaya et al., 1994
27	Steenkamp et al., 2000

the African continent outside of the Lake Victoria catchment. Finally, THg concentrations in hair and urine samples from human volunteers living near Lake Victoria are presented in Table 6, with the general THg exposure assessments detailed in Table 7.

DISTRIBUTION AND CONCENTRATIONS OF MERCURY IN LAKE VICTORIA

THg Concentrations in Lake Victoria Fish

The primary concerns regarding THg concentrations in fish from Lake Victoria are whether the fish are acceptable for consumption by residents in the Lake Victoria catchment and whether the THg concentrations are below international limits for export markets. International marketing limits in the European Union, the United States, and Canada (based on WHO guidelines) are 500 ng/g ww (U.S. EPA, 1997; Canadian Council of Ministers of the

TABLE 2. THg Concentrations in Fish From Across Lake Victoria, Using Citation Codes From Table 1

Species	Location	no.	Total weight (g)			THg (ng/g ww)			Citation
			Mean ± SD	Min	Max	Mean ± SD	Min	Max	
Clarias gariepinus (catfish)	Bugaia I.	1	130	—	—	5.7	—	—	2
	Thruston B.	1	5042	—	—	29.8			2
	Isagana R.	4	801 ± 498	66	1135	27.8 ± 23.5	14.0	630.0	13
	Winam G.	3	2167 ± 1850	300	4000	12.1 ± 9.0	4.9	22.1	3
Lates niloticus (Nile perch)	Bugaia I.	13	709 ± 1385	15	4700	65.9 ± 46.4	19.6	155.7	2
	Napoleon G.	17	702 ± 707	45	1950	115.2 ± 34.4	79.7	191.5	2
	Napoleon G.	15	767 ± 851	9	3150	90.5 ± 39.5	57.2	221.2	3
	Napoleon G.	22	991 ± 1276	9	4500	137.6 ± 46.5	90.8	251.7	12
	Thruston B.	8	2029 ± 2524	12	6500	60.3 ± 18.7	36.4	82.8	2
	Isagana R.	5	77 ± 22	53	98	108.0 ± 19.2	80.0	130.0	13
	Mwanza G.	6	31,833 ± 18,605	18,000	68,000	590.8 ± 364.2	166.0	1231.0	11
	Nungwe B.	3	350 ± 304	150	700	9.7 ± 2.5	6.9	11.7	6
	Nungwe B.	12	825 ± 644	100	2100	34.7 ± 23.2	9.0	87.0	11
	Speke G.	4	3700 ± 4297	600	10,000	108.0 ± 151.8	21.0	335.0	11
	Winam G.	12	—	—	—	95 ± 35	—	—	1
	Winam G.	20	5369 ± 14,236	14	65,000	55.7 ± 69.0	11.2	323.1	3
Oreochromis niloticus (Nile tilapia)	Napoleon G.	7	516 ± 429	80	1155	19.5 ± 18.1	8.1	59.3	2
	Napoleon G.	11	346 ± 453	65	1400	26.1 ± 14.0	11.1	59.7	3
	Napoleon G.	3	478 ± 589	80	1155	20.1 ± 12.4	10.7	34.1	12
	Thruston B.	6	155 ± 91	66	265	8.9 ± 6.2	1.7	15.9	2
	Isagana R.	10	366 ± 347	47	1060	59.6 ± 30.4	16.0	100.0	13
	Mwanza G.	5	1460 ± 669	1000	2600	9.0 ± 1.7	8.0	12.0	11
	Nungwe B.	5	390 ± 251	150	650	2.4 ± 0.4	1.8	2.9	9
	Nungwe B.	4	375 ± 50	300	400	10.0 ± 1.6	8.0	12.0	11
	Winam G.	12	—	—	—	10 ± 4	—	—	1
	Winam G.	15	1795 ± 885	300	2800	19.5 ± 12.1	3.4	43.1	3

TABLE 2. THg Concentrations in Fish From Across Lake Victoria, Using Citation Codes From Table 1 (*Continued*)

Species	Location	no.	Total weight (g)			THg (ng/g ww)			Citation
			Mean ± SD	Min	Max	Mean ± SD	Min	Max	
Protopterus	Napoleon G.	2	—	1000	2200	—	24.2	35.4	3
aethiopicus	Thruston B.	1	450	—	—	27.2	—	—	2
(lungfish)	Isagana R.	3	1826 ± 1124	528	2500	156.7 ± 85.0	70.0	240.0	13
	Nungwe B.	1	600	—	—	2.2	—	—	7
	Nungwe B.	1	124	—	—	19	—	—	11
	Winam G.	3	4167 ± 1179	2500	5000	20.3 ± 1.8	18.1	22.5	3
Rastrineobola	Bugaia I.	9	—	—	—	26.2 ± 5.6	17.2	33.7	2
argentea	Napoleon G.	1	—	—	—	27.1	—	—	12
(mukene/	Napoleon G.	3	—	—	—	16.3 ± 3.7	13.6	21.5	3
dagaa/omena)	Sweya V.	2	—	—	—	—	10.0	12.0	8

Note. I., island; B., bay; G., gulf; V., village.

TABLE 3. THg Concentrations in Water from Across Lake Victoria, Using Citation Codes from Table 1

Region	Site	Date	Depth (m) or stream site	THg (ng/L)	MeHg (ng/L)	Cit
Winam G.	Winam Gulf					
	Kisumu	12-Dec-98	0.5	4.5	—	3
			3	3.6	—	3
	Gingra Rock	14-Dec-98	0.5	2.9	—	3
			6	3.3	—	3
Napoleon G.	Prison	25-Oct-98	0.5	5.8	1	3
			15	3.2	0.7	3
	Prison Stream	Nov-95	Surface	—	0.14	12
	Water hyacinth		Surface	—	0.06–0.13	12
	Jinja Bay	18-Nov-98	0.5	3.9	—	3
			8.5	1.7	—	3
	Water hyacinth	18-Nov-98	0.5	2.3	0.2	3
			2	2.3	0.2	3
	Jinja Pier	29-Nov-98	0.5	2.8	—	3
			5	1.9	—	3
	Itome Bay	27-Oct-98	0.5	3.4	—	3
			16	1.9	—	3
	Bugaia Island	26-Oct-98	0.5	4	0.7	3
			41	1.8	0.3	3
	Bugaia Island	21-Oct-95	10 m	3.6	—	12
			40 m	15.5	—	12
Kitubulu Bay near Entebbe		03-Nov-98	0.5	3.2	—	3
			5	3	—	3
Speke G.	Speke Gulf (Nyankalalo)	23-Nov-96	4 m	<200	—	11
	Kiabakari mine (Musoma)	<1997	Spring water	1300	—	9
			Domestic tap water	300	—	9
			600 m downstream tailings	500	—	9
			1 km further	600	—	9
Emin Pasha G.	Nungwe Bay	27-Nov-96	4 m	<200	—	11
	Mugusu mine	<1997	Upstream washing site	1800	—	9
			Au washing site	1200	—	9
			2 km downstream	140	—	9
			3 km downstream	380	—	9
Mwanza G.	Mwanza (Point Capri)	30-Nov-96	2 m	<200	—	11
	Buyanhulu	<1997	Drinking water	135	—	10
			Au washing site	347	—	10
			Au washing water	679	—	10
	Upstream of Igonzela	Oct-97	Surface	n.d.–400	—	13
	Downstream of Igonzela		Surface	n.d.–100	—	13
	Mwakitolyo mine (Isanga)	<1997	Domestic pond water	1000	—	9
			Au washing site on lake	200	—	9

Note. <1997 Indicates that the date of sampling was not indicated in the study but is assumed to be prior to date of publication. n.d., Not detected.

TABLE 4. THg Concentrations in Soil (L) and Sediment (D) from Across Lake Victoria, Using Citation Codes from Table 1

Region	Site	Year	L/D	Description	THg (ng/g dw)	Citation
Napoleon G.	Jinja	'96	L	Agricultural topsoil	36.5 ± 13.5	3
	Itome Bay core	'95	D	Top 3 cm of core	180.5	12
Offshore	Far offshore core (V96-5MC)	'96	D	Top 3 cm of core	291.7	3
Speke G.	Speke G.	'96	D	4 m	<10	11
	Kiabakari mine	<'97	D	500 m downstream of tailings	340	9
			D	Upstream	160	9
			L	Background	49	9
Emin Pasha G.	Nungwe Bay	'96	D	4 m	30	11
	Mugusu mine		D	0.5 m	590	11
	Mugusu R. at Nungwe Bay		D	0.5 m	30	11
	Mugusu mine	<'97	D	Upstream	39	9
			D	Downstream after washing site	570	9
			D	Further downstream	420	9
			L	Background	110	9
			L	Au-Hg amalgam site	10,000	9
Mwanza G.	Bulyanhulu mine	'97–'98	D	Stream sediment	170–5350	13
	Downgradient of Igonzela Swamp		D	Stream sediment	10–20	13
	Mwakitolyo mine		L	Top 10 cm of core at gold processing site	2495	13
			L	Top 10 cm of core 80 m from processing	638	13
			L	30 cm depth of core 80 m from processing area	12	13
			L	Agricultural topsoil <50 m from processing site	1560	13
	Mwakitolyo mine	<'97	D	Domestic water pond	190	9
			D	Au washing site on L. Victoria	970	9
			L	Background	46	9
			L	Au-Hg amalgam site	28,000	9
	Magema mine (no lake outlet)	'96	D	0.5 m	1080	11

Note. <'97 Indicates that the date of sampling was not indicated but is assumed to be prior to date of publication.

Environment, 1999; European Economic Community, 1993). To protect vulnerable people, including pregnant women, those under 15 yr of age, and frequent fish consumers, WHO has recommended a lower guideline of 200 ng THg/g for those groups (World Health Organization, 1990).

TABLE 5. THg Concentrations in Environmental Samples from Across Africa

Type/species (concentration units)	Location	Number	Mean THg ± SD	Min	Max	Citation
Human urine (mg/L)	South Africa	65	—	<0.05	2.5	27
Human blood (mg/L)	Rabat, Morocco	377	9.5 ± 14.1	<5.0	139	19
Human blood serum in fishermen	Manzala L., Egypt	100	13.7 ± 2.8	—	—	25
Human blood serum in "control"		100	11.2 ± 1.5	—	—	25
Human hair (ppm)	KwaZulu-Natal, South Africa	14	<0.5	<0.5	<0.5	24
Air (ng/m^3)	Cape Peninsula, South Africa	2	—	1.05	1.52	17
Water (ng/L)	L. Naivasha, Kenya	5	5.3 ± 3.8	1.6	12.1	16
	L. Maryout (Mariut), Egypt	10	3.0 ± 0.01	—	—	18
Sediment (ng/g dw)	L. Malaŵi, Malaŵi	21	46	15	73	20
	Bahr El-Baqar, Manzala L.	3	120 ± 20	—	—	25
	El-Mataria City, Manzala L.	3	660 ± 10	—	—	25
	El-Mataria Village, Manzala L.	3	50 ± 10	—	—	25
	R. Wiwi, Ghana	8	211 ± 149	80	580	15
Soil (ng/g dw)						
Uncontaminated soil top 10 cm	Hammarsdale, South Africa	3	87.0 ± 47.3	75	150	22
Uncontaminated soil >90 cm		3	16.3 ± 20.3	n.d.	45	22
Effluent disposal site #1 top 10 cm		3	4740 ± 1714	6190	2332	22
Effluent disposal site #1 >90 cm		3	1006 ± 1264	90	2793	22
Plants (µg/g)						
Corn leaf	Mugusu mine, L. Victoria	1	0.17	—	—	11
Mixed "mufti" species	South Africa	10	1.0 ± 1.9	0.01	5.36	27

TABLE 5. THg Concentrations in Environmental Samples from Across Africa (*Continued*)

Type/species (concentration units)	Location	Number	Mean THg ± SD	Min	Max	Citation
Fish (ng/g ww)						
Lates niloticus	L. Nabugabo, Uganda	6	30.1 ± 9.7	10.6	42.2	2
Tilapia zilli		4	6.4 ± 3.4	1.9	10.6	2
Protopterus aethiopicus		1	7.5	—	—	2
Hydrocynus vittatus	L. Kariba, Zimbabwe	18	—	80	94	23
Sargochromis codringtonii		20	—	4	26	23
Limnothrissa miodon (w)		—	—	n.d.	69	23
Heterobranchus isopterus	R. Wiwi, Ghana	9	350 ± 180	160	720	15
Clarias gariepinus		4	420 ± 60	370	510	15
Stolothrissa tanganyikae (w)	L. Tanganyika, Burundi	50	60 ± 30	—	—	26
Lates stapersii		50	40 ± 20	—	—	26
Oreochromis karongae	L. Malaŵi, Malaŵi	7	3.9 ± 2.1	—	—	21
Oreochromis lidole		7	7.0 ± 1.4	—	—	21
Engraulicypris sardella		11	11 ± 4.3	—	—	21
Opsaridium microlepis		7	92 ± 51	—	—	21
Bathyclarias nyasensis		4	55 ± 42	—	—	21
Bagrus meridionalis		10	43 ± 34	—	—	21
Ramphochromis cf. ferox		3	200 ± 160	—	—	21
Ramphochromis cf. macrophthalmus		5	20 ± 10	—	—	21
Clarias gariepinus	u'Mgeni River, South Africa	3	403 ± 37	360	450	24
Micropterus salmoides		4	345 ± 15	330	360	24
Clarias gariepinus	Inanda Dam, South Africa	5	200 ± 6	190	210	24
Micropterus salmoides		5	110 ± 72	50	250	24
Clarias gariepinus	Nagle Dam, South Africa	5	140 ± 71	50	240	24
Micropterus salmoides		5	370 ± 232	10	660	24
Mugil spp.	Manzala L., Egypt	6	0.78 ± 1.0	—	—	25
Oreochromis niloticus		6	0.78 ± 1.0	—	—	25

Note. For fish, muscle tissue was analyzed, except for smaller whole fish (w). n.d., Not detected. Citation codes are From Table 1. L., lake; R., river.

TABLE 6. Hg Concentrations in Lake Victoria Human Hair and Urine Samples

Region	Location	Year	Who	Max number	Hair (ppm)			%MeHg hair			Urine (μg/L)			Citation
					Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	
Winam	Kumuango mines	1998	7 Males, 2 females	9	1.4 ± 1.0	0.7	3.5	—	—	—	—	—	—	6
	Sori Beach		8 Males, 4 females	12	2.1 ± 1.6	0.7	5.6	—	—	—	—	—	—	6
	Homa Bay		5 Males, 8 females	13	4.5 ± 11.5	0.6	42.8	—	—	—	—	—	—	6
	Dunga Beach		10 Males, 9 females	19	48.5 ± 206	0.2	900	—	—	—	—	—	—	6
	Kisumu City		12 Females	12	145 ± 219	1.1	603	—	—	—	—	—	—	6
Emin Pasha	Mugusu	1995	Gold extractors	9	1.7 ± 1.5	0.4	5.4	23.4 ± 19.2	n.d.	69.1	155.4 ± 129.3	n.d.	411.4	7
			Non-gold worker males	2	—	n.d.	1.5	—	n.d.	21	—	3.1	4.5	7
			"High" female	1	214.2	—	—	0.1	—	—	8.8	—	—	7
			Female	2	—	0.4	0.4	—	30.7	63.3	—	1.3	1.9	7
			"High" pregnant female	1	342.1	—	—	0.5	—	—	27.3	—	—	7
			Pregnant female	2	—	n.d.	n.d.	—	n.d.	n.d.	—	2	21.7	7
	Nungwe	1995	Female	5	0.31 ± 0.09	0.2	0.4	49.0 ± 27.1	n.d.	82.1	0.1 ± 0.2	n.d.	0.7	7
			Male	7	0.22 ± 0.16	n.d.	0.4	27.2 ± 20.4	n.d.	59	3.2 ± 4.5	0.9	14.1	7
Mwanza	Bulyankulu	1997–98	Control	43	0.5 ± 0.4	0.1	1.8	—	—	—	17.6 ± 17.0	2.4	61	4
											(6.2 ± 4.9)	(0.8)	(16)	14
			Miners	12/55	0.9 ± 0.6	0.1	2.3	—	—	—	58.9 ± 66.4	2.2	320	4
											(23.2 ± 20.9)	(1.3)	(97)	14
			Goldsmiths	4	—	—	—	—	—	—	11.5 ± 9.0	4.6	27	4
											(3.3 ± 1.3)	(1.3)	(5)	14

TABLE 6. Hg Concentrations in Lake Victoria Human Hair and Urine Samples (*Continued*)

Region	Location	Year	Who	Max number	Hair (ppm)			%MeHg hair			Urine (µg/L)			Citation
					Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	
			Fishermen +farmers	36	0.2±0.1	0	0.6	—	—	—	(control)	—	—	4
	Isanga River	1997	"High" female farmer	1	—	—	4.9	—	—	—	—	—	—	4
	Katente	1997	"High" female	2	—	185	288	—	—	—	—	—	—	4
Mwanza	Gold mines	1996–97	205 Males, 18 females	223	—	1.6 ± 2.0	81.9 ± 241	—	1	20.5	—	—	—	5
	Fishing villages		113 Males, 21 females	134	—	1.0 ± 0.6	28.9 ± 98.2	—	0.2	1.7	—	—	—	5
	Mwanza City		21 Males, 13 females	34	—	3.4 ± 7.0	59.1 ± 129	—	1.1	4.7	—	—	—	5
Mwanza	Mwanza City	1997	Male	6	1.1 ± 0.7	0.3	2.4	3.4 ± 3.3	0.4	10.2	0.5 ±. 2	0.3	1	10
			Female	6	121.1 ± 138.0	0.4	390	1.7 ± 2.8	0.002	7.7	23.8 ± 35.8	0.3	101.4	10
	Dosoma		Male	2	—	1.4	4.6	—	0.9	8.2	—	0.6	0.9	10
	Mwakitolyo mines		Male	8	3.3 ± 1.5	1.6	6.2	1.0 ± 0.6	0.1	2	56.7 ± 47.1	1.3	157.6	10
			Female	4	125.1 ± 211.3	0.7	491	1.9 ± 2.2	0.01	5.6	22.4 ± 33.7	0.8	80.6	10

Note. Urine values in brackets are expressed as µg Hg/g creatinine. n.d., Not detected. Citations from Table 1.

TABLE 7. Human Exposure Estimates and Factors Used in Estimates

	Adult (20+ yr)	Child (5–11 yr)
Factors used in estimates:		
Body mass (kg)	70	27
Drinking water (L/d)	2	1
Inhalation (m^3/d)	23	12
Soil ingestion (mg/d)	35	50
Soil adhered to skin (mg/d)	8700	5800
Soil geophagy (mg/d)	28	28
Fish (g/meal/d)	200	100
Nile perch meals (per month)	1	0.5
Nile tilapia meals (per month)	16	16
Body surface area (cm^2)	18,200	9660
Bathing and swimming time (min/d)	30	30
Application of skin-lightening cream (g/d)	1	n.a.
Permeability constant (cm/h)	1	1
Estimated THg intake (away from Au fields)		
Drinking water	0.09	0.11
Inhalation	0.35	0.47
Nile perch consumption	9.52	6.17
Nile tilapia consumption	30.48	39.51
Bathing exposure	0.39	0.53
Soil ingestion	0.02	0.07
Soil-skin exposure	4.54	7.84
Total EDI	45.38	54.70
Estimated THg intake (near Au fields)		
Drinking water	2.86	3.70
Inhalation	0.35	0.47
Nile perch consumption	9.52	6.17
Nile tilapia consumption	30.48	39.51
Bathing exposure	13.00	17.89
Soil ingestion	0.03	0.09
Soil-skin exposure	6.21	10.74
Total EDI	62.45	78.57
Estimated THg intake from soil geophagy		
Away from the goldfields	14.2	59.6
Near the goldfields	20	82.5
Estimated THg intake from lightening creams		
European-made beauty soaps	8.5×10^4	n.a.
African-made beauty soaps	19.36	n.a.

Note. Units for estimated THg intake and estimated daily intake (EDI) are ng THg/kg body mass/d. The Health Canada guideline for tolerable daily intake (TDI) of THg is 710 ng/kg/d (CCME, 1999).

The three commercially important fish species in Lake Victoria are *Lates niloticus* (Nile perch), *Oreochromis niloticus* (Nile tilapia), and *Rastrineobola argentea*. Two other fish species were also included, the popular local delicacies *Clarias gariepinus* (catfish) and *Protopterus aethiopicus* (lungfish; Table 2). Nile perch is the top trophic predator in Lake Victoria and consumes small fish, including its own young, and the freshwater prawn *Caridina nilotica* (Campbell, Hecky & Wandera, 2003). Nile tilapia is a detritivore that will occasionally eat invertebrates and small *C. nilotica* (Balirwa, 1998). *Rastrineobola argentea* (mukene, omena, or dagaa) is a small, silvery pelagic cyprinid found in schools. Catfish and lungfish are omnivores frequently caught around near-shore macrophyte beds and will eat small fish, molluscs, *C. nilotica*, and plant detritus (Greenwood, 1966).

The trophic status and dietary patterns of each species are very important in terms of how much THg is bioaccumulated by individual fish. The more trophic transfers (steps between the higher trophic predators and the lower trophic prey), the more Hg will biomagnify in the top trophic predator; top predators in longer food webs will bioaccumulate more contaminants than the same species in a shorter food web (Cabana et al., 1994). Food-web studies using $\delta^{15}N$ values of fish as an indicator of trophic level (for example, top trophic Nile perch will have higher $\delta^{15}N$ values) indicated that THg biomagnifies through the food webs of Napoleon and Winam Gulfs, Lake Victoria, at a consistent rate (log THg–$\delta^{15}N$ slopes=0.17; Campbell, Hecky & Wandera, 2003). This is comparable to published biomagnification rates (log THg–$\delta^{15}N$ slopes=0.17 to 0.4) for the temperate lakes in North America, and tropical lakes in Africa and Papua New Guinea (Kidd et al., 1999, 2003; Bowles et al., 2001; Campbell, Hecky & Wandera, 2003). The implication is that THg bioaccumulation remains similar across different aquatic ecosystems, regardless of productivity and the latitude of the ecosystem (Campbell, Hecky, Nyaundi et al., 2003). Relatively higher THg concentrations in a particular fish species from different locations in Lake Victoria and other African lakes are related to higher ambient MeHg concentrations and longer food-web length, not to any inherent variation in the food-web structure affecting the rate of biomagnification.

Nile tilapia THg concentrations (<100 ng/g; Table 2 and Figure 3A) are consistently below the WHO limit, regardless of size, and are safe for frequent consumption by the general population. *Rastrineobola argentea* also have THg concentrations (10 to 33.7 ng/g; Table 2) that are consistently below all limits. Nile tilapia and *R. argentea* are the most popular fish species for consumption by people in the region (SEDAWOG, 1999) and, fortunately, no regulatory advice for THg is recommended for these frequently consumed species.

Nile perch are usually below the WHO limit of 200 ng/g (Figure 3B), although when they approach a weight of 10 kg, THg concentrations begin to exceed that limit (Figure 3B). A few Nile perch from Napoleon Gulf in Uganda reach the WHO limit at 3 kg, raising questions about the methylation rates of Hg compounds in that gulf (Campbell, 2001; Campbell, Hecky, Nyaundi et al., 2003). It is recommended that the at-risk groups avoid Nile perch heavier than 5 to 10 kg, depending on where they are caught (Napoleon Gulf or elsewhere),

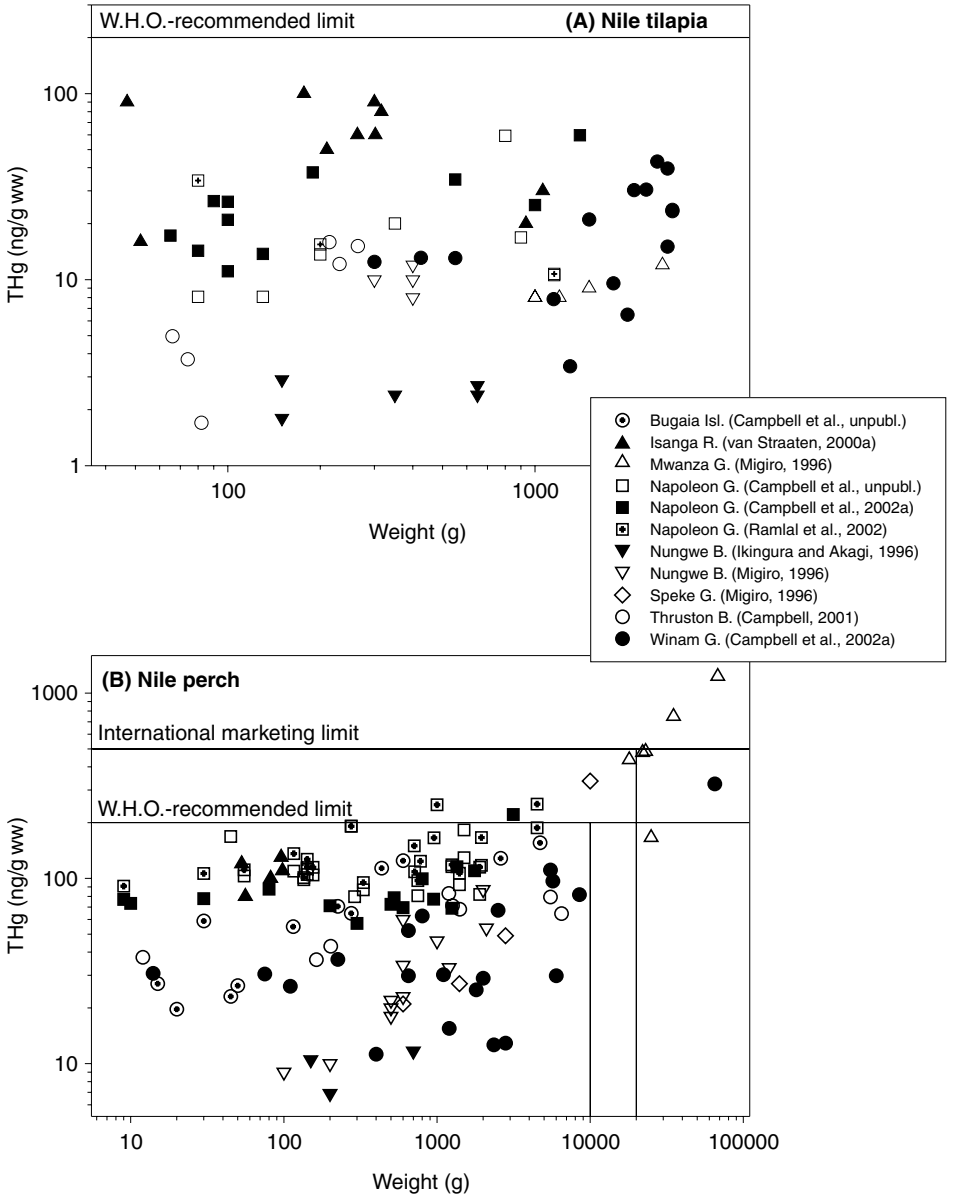

FIGURE 3. THg concentrations versus weight for (A) Nile tilapia and (B) Nile perch. Note the logarithmic scale. The horizontal lines indicate WHO (200 ng/g) and international (500 ng/g) marketing limits.

to reduce their risk. Due to the high cost of Nile perch and the high demand for large fillets for export, people around Lake Victoria rarely consume Nile perch. Only a few large Nile perch (20 kg) bought at the Mwanza Market exceeded international marketing limits (Migiro, 1996). Such large fish are increasingly rare

in Lake Victoria due to overfishing (Ogutu-Ohwayo, 1999) and self-limitation by cannibalism (Campbell, Hecky & Wandera, 2003). European Union (EU) testing protocols for THg in fish require that "table-sized portions" of 10 randomly selected fillets be pooled and homogenized for analysis, thereby averaging the THg concentrations of 10 fish (European Economic Community, 1993). This method does not take into account the size of the fish or occasional elevated THg concentrations in individual fish. The fact that those regulatory samples have consistently met the guidelines for EU import (Meyer & Kruse, 1998; Tanzania Fisheries Department, 1999) indicates that these large individual Nile perch with elevated THg concentrations are now rare in both the fishery and the international marketplace and currently do not present a regulatory issue.

A number of fish from the Isanga River near Mwanza Gulf are relatively contaminated compared to the same species elsewhere. Some of the highest THg concentrations (and the highest mean THg value) for Nile tilapia are from that system (Figure 3A and Table 2). One catfish from the Isanga River exceeded international marketing limits (630 ng/g), while a lungfish from the same region exceeded the WHO limit (240 ng/g). Other Isanga River catfish and lungfish THg concentrations approached the WHO limit (Table 3). Lungfish and catfish sampled from other regions of the lake have much lower THg concentrations (~20 ng/g). van Straaten (2000a) pointed out that those fish with higher THg concentrations were collected near the Ag-Hg amalgamation sites in the goldfields, while the less-contaminated fish were caught near Smith Sound of Mwanza Gulf, away from the amalgam processing sites. The actual source and the pathway of uptake of the THg in lungfish and catfish from the Isanga River are currently unknown. If the sediments in the system are contaminated with Hg as a result of Au amalgamation, the fish could be obtaining the THg by consumption of contaminated benthos. Alternatively, elevated sediment levels could result in elevated Hg levels in the water at the sediment-water interface and the fish could be obtaining the THg by direct gill uptake. Given that the fish from other regions of Lake Victoria show lower THg concentrations (Table 2), it is apparent that fish from the Isanga River deserve closer examination.

THg concentrations in fish from Lake Victoria are comparable to those in fish from other African freshwater lakes. The fish species that are trophically analogous to Lake Victoria Nile perch are *Hydrocynus vittatus* in Lake Kariba, *Lates stapersii* in Lake Tanganyika, and *Ramphochromis* spp. in Lake Malaŵi. These species have mean THg concentrations ranging from 20 to 200 ng/g (Table 5), consistent with the range of 7 to 1231 ng/g for Lake Victoria Nile perch (Table 2). *Oreochromis* spp. from Lake Malaŵi and *Sargochromis codringtonii*, a molluscivore from Lake Kariba, have mean THg concentrations ranging from 4 to 7 ng/g (Table 5), somewhat lower than the trophically analogous Nile tilapia in Lake Victoria (2 to 100 ng/g; Table 2). *Clarias gariepinus* and *Heterobranchus isopterus* from Wiwi River in Ghana and *C. gariepinus* from South Africa have THg concentrations (160 to 720 ng/g; Table 5) similar to those for *C. gariepinus* and *P. aethiopicus* from Isanga River, but higher than analogous species from other regions of Lake Victoria (*C. gariepinus*; Table 2) or Lake Malaŵi (*Bathyclarias*

nyasensis; Table 5). *Stolothrissa tanganyikae* from Lake Tanganyika and *Engraulicypris sardella* from Lake Malaŵi (11 to 60 ng/g; Table 4) share similar THg concentrations with those for *R. argentea* (10 to 34 ng/g) in Napoleon Gulf, Lake Victoria. This suggests that the fish species of Lake Victoria do not have particularly elevated or depressed THg concentrations relative to analogous species in other African lakes, despite those aquatic ecosystems having quite different limnological conditions (Bootsma & Hecky, 1993).

THg Concentrations in Lake Victoria Waters

Canadian drinking water standards specify that no more than 100 ng/L THg be present in potable water (Health Canada, 1996). In the Laurentian Great Lakes of North America, the water quality criterion (1.8 ng THg/L) for the protection of aquatic life is lower than the potable water value in both Canadian and U.S. waters (U.S. EPA, 1997; Canadian Council of Ministers of the Environment, 1999). For the protection of wildlife and birds that feed upon fish, a limit of 12 ng/L, which takes food-chain transfer into account, has been recommended (Nichols et al., 1999). In Uganda, the limit for wastewater entering the lake is 10,000 ng/L (Republic of Uganda, 1999). In Tanzania, the drinking water and industrial/agricultural THg limits have been set at 1000 ng/L and 2000 ng/L, respectively (DHV Consultants BV et al., 1998). With such a broad range of limits and guidelines available, it is obvious that an international consensus has not yet been reached with regard to safe limits of THg in water. For this review, the Canadian drinking water standards (100 ng/L; Health Canada, 1996), which are similar to those of WHO (World Health Organization, 1989, 1990), and the Canadian standard for the protection of aquatic life (1.8 ng/L, CCME, 1999) were used as the basis of evaluation for THg levels in Lake Victoria.

In Lake Victoria, nearly all water samples have THg concentrations (0.7 to 200 ng/L, Table 3) that do not exceed the Health Canada standard (Table 3) and are generally safe for drinking and bathing. Most THg water samples, however, do exceed the aquatic life protection limit of 1.8 ng/L and are higher than published THg concentrations (0.1 to 1.0 ng/L) measured in the Laurentian Great Lakes and Lake Baikal (Meuleman et al., 1995; Mason & Sullivan, 1997; Amyot et al., 2000). Elevated water THg concentrations may be common in African lakes as the water THg concentrations in northern Lake Victoria are similar to those in Lake Naivasha in Kenya and Lake Maryout/Mariut in Egypt (1.6–12.1 ng/L; Table 5). Water samples collected from inland streams and ponds near Au mines and ore processing sites, including domestic and drinking water sites, frequently showed THg concentrations (140–1800 ng/L) in excess of the Health Canada standard and are probably not safe for frequent bathing or drinking by humans or wildlife.

THg concentrations in northern Lake Victoria are correlated with chlorophyll-*a* concentrations, suggesting that the phytoplankton of Lake Victoria play an important role in THg cycling (Campbell, 2001). It has been suggested that Hg bound to oxyhydroxides of soil particles in the lake may be released upon reduction in the hypoxic zone in deeper waters (Campbell, 2001), but this

requires further detailed investigation of the biogeochemistry of THg in the lake. There are concerns that the apparently low bioavailability of THg from the water column in Lake Victoria might increase in the near future because the water column is becoming anoxic (Hecky et al., 1994). Anoxic waters favor methylating bacteria relative to demethylators, which could result in a net increase of MeHg in the water column (Morel et al., 1998). In addition, the rapidly increasing human population is introducing additional pressures, such as erosion, biomass burnings, and increased use of Hg-containing products (petrol, skin-lightening cream, and agricultural biocides) to the Lake Victoria catchment (Campbell, 2001). Unquantified THg sources to the lake environment need to be assessed, particularly waste disposal (burning and decomposition) in towns (Nriagu, 1992) and the runoff wastewater contaminated by skin-lightening cream into the lake (Harada et al., 2001). Relatively high THg concentrations in Lake Victoria waters, compared to temperate Great Lakes (Campbell, 2001), should logically lead to higher concentrations in fish, but this is not occurring. The low THg concentrations in fish have been attributed to four probable factors: short food-chain length, increased growth dilution in fast-growing fish including higher tissue turnover in tropical biota, biomass dilution in eutrophic Lake Victoria, and the biogeochemistry of Lake Victoria (Campbell, Hecky, Nyaundi et al., 2003). The low THg concentrations in fish are positive for fish consumers, but nonetheless, the rapid changes occurring in the Lake Victoria catchment and the relatively high THg concentrations in the water indicate that there is no reason for complacency about the THg issue facing the lake. Recent research in temperate lakes demonstrated that the proportion of MeHg to other Hg compounds can change with environmental conditions, including declining oxygen concentrations, even if THg concentrations do not change (Hecky et al., 1991; St. Louis et al., 1994; Watras et al., 1995; Regnell et al., 2001). Those studies indicate that Lake Victoria is at risk for elevated MeHg in its biota if steps are not taken to prevent any environmental shifts that favor increased methylation rates.

Wetlands can be an important factor in preventing THg from Au-Hg amalgamation sites from entering the lake, as THg can be accumulated and retained in the organic-rich sediments. For example, the water entering Mwanza Gulf downstream of the Igonzela Swamp contained 100 ng THg/L, but water sampled near Au mines prior to the Igonzela Swamp had 400 THg/L (van Straaten, 2000a; Table 3). However, the holding capacity of the wetlands around Lake Victoria is unknown, and it is not known how long the wetlands can hold THg before their retention capacity is reached and the THg is flushed into the lake. Temperate studies have shown that the rich organic environment of wetlands can actually promote methylation of THg, thereby increasing MeHg concentrations, which could be flushed into the lake (St. Louis et al., 1994). It has been demonstrated that heavy metals stored in polluted wetlands near Kampala, Uganda, and Kisumu, Kenya, have been flushed into Lake Victoria (Onyari & Wandiga, 1989; Kiremire, 1998), and there is no reason to suggest that THg or MeHg will behave differently.

THg Concentrations in Lake Victoria Sediments and Soils

In the main lake, the lowest THg concentrations in surface sediments were found in Tanzanian waters (<10 ng/g in Speke Gulf, 10 to 20 ng/g in Smith Sound, Mwanza Gulf, and 30 to 39 ng/g in Emin Pasha Gulf; Table 4). The highest sediment THg concentrations found in areas not obviously affected by mining activity were in the top layers of sediment cores collected from Napoleon Gulf (Itome core, 181 ng/g dw) and an offshore site in the center of the lake (V96-5MC core, 292 ng/g; Table 4). These values are within the THg concentrations seen for other African aquatic ecosystems, which range from 46 ng/g in Lake Malaŵi to 210 ng/g in Wiwi River (Table 5). Sediment samples from Tanzanian ponds directly influenced by gold mining activity show elevated concentrations (160 to 5350 ng/g) relative to the low values from sediments in southern Lake Victoria (Table 4), pointing to the importance of Au processing as a local (but not lakewide) source of THg. Those sediments have elevated THg concentrations similar to those seen for contaminated Manzala Lake in Egypt (120 to 660 ng/g; Table 5).

The apparently rapid increase in THg concentrations in lake sediments away from Au-processing sites, especially in the surface sediments in a remote far-offshore site, points to sources other than the direct contamination by Au-Hg amalgamation in Tanzania. In 1995 and 1996, two cores were collected 165 km apart in Lake Victoria, one from Itome Bay, the other from the middle of the lake (V96-5MC; Figure 2). These cores, analyzed for THg in two separate laboratories (Campbell, 2001; Ramlal et al., 2003), are similar in their THg concentration profiles (Figure 4). In Core 103 from Kenyan waters (Figure 2), there has been an increase in the polycyclic aromatic hydrocarbons (PAHs) in recent times (Lipiatou et al., 1996). PAHs are combustion by-products that can arise from petroleum and biomass burning combustion, and the types of PAHs most prevalent in Core 103 are associated with biomass burnings and soil erosion (Lipiatou et al., 1996). Exponential increases in the burning of organic material, both for fuel and to clear agricultural land, due to an expanding population in the Lake Victoria catchment (Bootsma & Hecky, 1993), may be an important source of THg to the lake. Plants, when burned, release THg to the atmosphere (Freidli et al., 2001), and biomass burnings are very prevalent in Africa (Dwyer et al., 2000). It is estimated that the current rate of biomass burning in the Lake Victoria catchment releases about 8 to 24 tons of THg per year to the atmosphere (Campbell, 2001). This is larger than the estimated annual emission rate of 3 to 4 tons from gold mining activities (van Straaten 2000a). Overall, it appears that gold mining is a relative minor regional source of THg to the entire lake (van Straaten, 2000a; Campbell, 2001). THg analysis of wet precipitation samples indicated that about 0.7 to 4.5 tons/yr of THg is deposited to the lake in rain (Campbell, 2001). The dry deposition rate for THg is unknown, but an atmospheric phosphorus deposition study in Tanzania estimated that roughly 75% of the phosphorus input is derived from biomass burnings and deposited dry particulates (R. Tamatamah, personal communication,

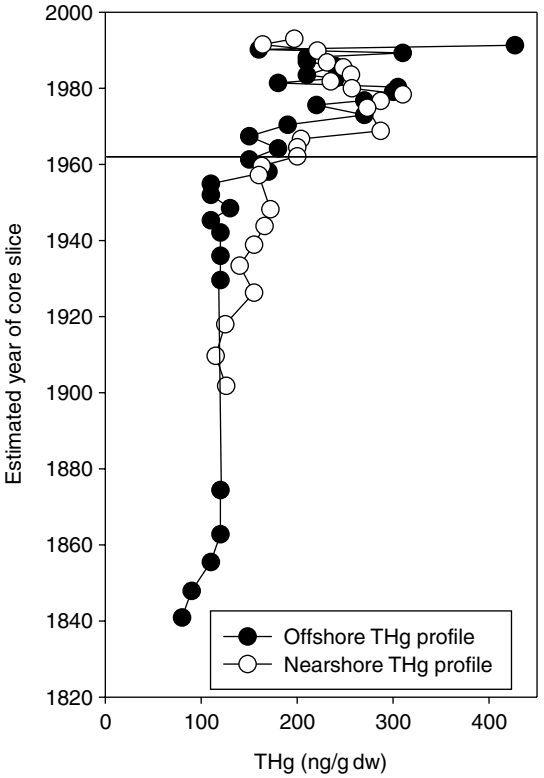

FIGURE 4. ^{210}Pb-dated core THg concentration profiles. The cores diagrammed here are from nearshore Itome Bay (11 on map in Figure 1) and offshore V96-5MC site (12 in Figure 1) and have been discussed in Campbell (2001).

Department of Biology, University of Waterloo, Waterloo, Canada). Extrapolation to THg suggests that 6 to 18 tons/yr may be deposited on the lake from biomass burnings. Atmospheric THg sources and deposition rates for the Lake Victoria catchment need verification to confirm the importance of biomass burnings as a THg source.

The Canadian soil criterion for the protection of humans is 100 ng THg/g dry weight (Canadian Council of Ministers of the Environment, 1999). Most soil samples collected around Lake Victoria and at a distance from Au-Hg amalgamation sites were below this criterion (30 to 50 ng/g; Table 4). The background concentrations are within the range for northern hemisphere countries (~1 to 330 ng/g) but are lower than those for tropical soils in the Amazon Basin (60 to 219 ng/g) (Roulet & Lucotte, 1995; Roulet et al., 1998). However, surface soil samples within a 100-m radius of Au-Hg amalgamation sites considerably exceed the criterion. THg concentrations range from 638 ng/g at a site 80 m from an amalgamation site near the Mwakitolyo mine to 2495 to

28,000 ng/g at various amalgamation sites around Emin Pasha and Mwanza Gulfs (Table 4).

Soil samples from a depth of 30 cm taken from a site 80 m from the Mwakitolyo amalgamation site contained very low THg concentrations (12 ng/g) relative to the top 10 cm (638 ng/g). This has been attributed to the strong affinity of Fe oxyhydroxides for Hg compounds (van Straaten, 2000a). Similar results also been reported for soil cores from a contaminated site in South Africa, where surface and subsurface soil slices showed THg concentrations of 6200 ng/g and 90 ng/g, respectively (McNab et al., 1997; Table 5). Oxyhydroxide particulates, a common soil component, are particularly abundant in the weathered red tropical soils of Africa and South America (Karim & Adams, 1984; Reedman, 1984; Roulet & Lucotte, 1995; Roulet et al., 1998). Extensive soil geochemistry research in the Amazon basin has indicated that Fe and Al oxyhydroxides are important binding sites for THg and that upon entering water by erosion, the oxyhydroxides are reduced, releasing THg (Roulet & Lucotte, 1995; Roulet et al., 1998). This has been confirmed by soil studies near Jinja (Uganda) and Morogoro (Tanzania) that showed a strong correlation between clay particles, ferric oxides, and THg (Semu et al., 1986; Campbell, 2001). Oxyhydroxides and oxides in soils may be important factors in retaining THg from entering the lake, in addition to the buffering capacity of wetlands. However, soil erosion becomes an additional concern as increasing erosion rates around the lake introduce more THg to the water column (Campbell, 2001).

HUMAN CONCERNS

THg Concentrations in Humans

Despite the relatively high THg concentrations in water and sediments, THg concentrations were low in humans (Table 6), indicating either a low exposure to MeHg or rapid depuration of inorganic Hg (IHg). IHg is rapidly excreted through urine and faeces (Ratcliffe et al., 1996). MeHg, however, has a longer residence time in humans and tends to assimilate in cells (Sweet & Zelikuff, 2001; Ratcliffe et al., 1996). Because both IHg and MeHg act on immune and neurological responses, the most obvious sign of Hg poisoning is the onset of neurological disabilities, including tremors, extreme irritability, depression, and numbness of extremities (Sweet & Zelikuff, 2001; Ratcliffe et al., 1996). However, responses to THg and MeHg exposure are highly variable among individuals, and neurological and psychological examinations may not always indicate THg toxicity (Clarkson, 1997). The best method to assess Hg exposure in humans is to collect bodily specimens, most commonly hair and urine in Africa. Urine is the most reliable indicator of inhaled Hg vapor, which may emanate from Au-Hg amalgamation, while hair samples are good indicators of THg that has been consumed in food or absorbed through skin (Clarkson, 1997). For urine samples, WHO and national regulatory agencies prefer to use milligrams THg per gram creatinine in urine for their recommended criterion

because this avoids the problem of diluted or concentrated urinary output in the subjects (World Health Organization, 1990). When urinary THg concentrations exceed 100 mg THg/g creatinine, exposed individuals often exhibit the symptoms of Hg poisoning. Individuals with urinary THg concentrations between 30 and 100 mg THg/g creatinine may have less severe symptoms that are not apparent on clinical examination. Based on this, WHO has recommended an upper limit of 50 mg THg/g creatinine in urine for most individuals and 2 mg/g in hair (World Heath Organization, 1989, 1990). A standard of 25 mg THg/g creatinine for occupationally exposed individuals is applied in many developed countries (DHV Consultants BV et al., 1998). Based on studies of the major THg poisoning event in Minamata, Japan, some researchers have suggested 50 mg/g in hair as the threshold concentration for the onset of Hg poisoning (Harada et al., 1999).

Most Lake Victoria studies have expressed THg in urine samples from human volunteers as milligrams THg per liter urine, making it difficult to compare average THg concentrations with international criteria. Opportunely, one extensive study has collected creatinine-normalized THg urinary data from human volunteers living near Mwanza Gulf (DHV Consultants BV et al., 1998; van Straaten, 2000b). The author has made available the same data expressed as unnormalized urinary THg concentrations for this review to enable comparisons with other studies and rough extrapolation to WHO criteria (DHV Consultants BV et al., 1998).

The highest creatinine-based THg concentration (172 mg THg/g creatinine) was measured in a 29-year-old male who was employed in Au-Hg amalgam refining daily for at least 6 yr (DHV Consultants BV et al., 1998; van Straaten, 2000b). Miners and goldsmiths tended to have high creatinine-based THg concentrations relative to the control groups (fishermen, farmers, town workers); 36% of the miners exceeded the WHO guidelines, indicating the potential for widespread THg posioning in this occupationally exposed group (DHV Consultants BV et al., 1998; van Straaten, 2000b). The unnormalized urinary THg concentrations (Table 6) for occupationally exposed people ranged from below the detection limit (n.d.) to 411 mg THg/L (Ikingura & Akagi, 1996; Kahatano & Mnali, 1997; DHV Consultants BV et al., 1998). Fishermen and their families, despite their high intake of fish, tended to have low urinary THg output concentrations (14.1 mg/L), well within the control group limits (Ikingura & Akagi, 1996; DHV Consultants BV et al., 1998). A South African study (Steenkamp et al., 2000) of patients who used mufti, traditional medications, demonstrated very low THg urine concentrations (<0.05–2.5 mg/L; Table 5). This suggests that the fishermen and other control groups from Mwanza Gulf may still have THg concentrations slightly elevated above those of other non–fish-eating Africans.

Hair THg concentrations in the surveys revealed similar patterns (Table 6) with comparatively low THg concentrations in fishermen, in their families, and in control groups (Ikingura & Akagi, 1996; Kahatano & Mnali, 1997; van Straaten, 2000b). Only one out of all surveyed fishermen in all studies showed

hair THg concentrations exceeding the "Minamata threshold" criterion of 50 mg/g (cause unknown), and most fishing village residents in Tanzania had hair THg concentrations below the WHO criterion of 2 mg/g (Table 6). Around Winam Gulf, hair samples frequently exceeded the WHO criterion, but whether this is due to a high fish diet, higher contamination in the gulf region, or other unknown factors is unclear. Ikingura and Akagi (1996) claimed that fishermen and their families, despite low THg concentrations in their hair, have a higher proportion of MeHg than other groups, indicating that fish is the primary source of mercury for those people. Only the females in fishing villages showed a higher proportion of MeHg (49%) compared to fishermen (27%) and miners (23%; Table 6); without knowing the proportion and type of fish in each group's diet it is difficult to draw conclusions. Miners and goldsmiths tended to have somewhat higher THg concentrations in hair than the control group, usually exceeding the WHO criteria of 2 mg/g (van Straaten, 2000b). Even that group, however, shows concentrations below the Minamata threshold limit of 50 mg/g. Some occupationally exposed gold mine workers showed very high hair THg concentrations exceeding the threshold criteria. They also showed symptoms of organic Hg poisoning (Harada et al., 1999), emphasizing the extreme occupational hazards of gold mining in Tanzania.

Extremely high hair THg concentrations were measured for some non-occupationally exposed individuals, almost all of them female (Ikingura & Akagi, 1996; Kahatano & Mnali, 1997; Harada et al., 1999, 2001; van Straaten, 2000b). The THg concentrations in hair ranged from 48 to 900 ppm in those individuals (Table 6), exceeding the Minamata threshold limit of 50 ppm. The THg content primarily consisted of inorganic Hg (IHg), suggesting a nondietary souce of exposure; if the Hg was derived from food or dental amalgam fillings, then the hair samples should contain mostly MeHg (although many people in East Africa do not have dental amalgam fillings). Those high hair IHg concentrations were linked to the use of skin-lightening preparations and disinfectant soaps illegally exported from Europe and sold in East Africa (Harada et al., 2001). Clinical examinations found some links between mild poisoning symptoms and the use of the high-IHg-containing European-made creams (Harada et al., 2001). African-made creams did not have such high IHg concentrations, making them somewhat safer for use. Such frighteningly high concentrations in exposed individuals, especially pregnant women—one pregnant woman was found to have IHg hair concentration of 342 ppm (Table 6)—are dangerous and cannot be ignored in a human exposure assessment.

Human Exposure Estimates

The factors used in the human exposure estimates were drawn primarily from Health Canada guidelines (Health Canada, 1995) and modified for the lifestyle patterns around Lake Victoria. Modifications included increased consumption rates for fish (Nile tilapia and Nile perch; Campbell, 2001), inclusion of soil geophagy (Smith et al., 2000), and inclusion of skin-lightening creams that contain inorganic Hg (Harada et al., 2001). Two exposure assessments

were completed, one for individuals living around the northern part of the lake away from the gold fields, and one for subjects living in the south in closer proximity to the gold fields. Only the water and soil THg concentrations were different for "away" and "near" goldfield estimates (3 and 100 ng/L and 30 and 50 ng/g, respectively). The same THg concentrations for Nile tilapia (20 ng/g), Nile perch (100 ng/g), and air (1.05 ng/m^3 from Brunke et al., 2001) were used for both locations. The mean Hg concentrations for skin-lightening cosmetic preparations made in Europe (mean, 5.96 mg/g) or Africa (mean, 0.001 mg/g) were obtained from Harada et al. (2001). The use of common data is justified since there was considerable overlap in the THg values in fish, and the air THg values are unknown for Lake Victoria. The THg values in skin-lightening creams would be the same regardless of country because the same brands are available throughout the Lake Victoria catchment. Since fish is the most important dietary source of MeHg to humans (World Health Organization, 1990; Clarkson, 1997), it was assumed that other common dietary items such as chicken, vegetables, and red meat provided negligible amounts of Hg to human diets. Table 7 outlines the estimated THg exposure of a 70-kg adult and a 27-kg child living in the Lake Victoria region and their total estimated daily intake (EDI) from different exposure routes. The Health Canada tolerable daily intake (TDI) is 710 ng THg/kg body weight per day. It should be noted that the exposure estimates are conservative, since 100% absorption is assumed regardless of the exposure route or form of Hg.

Most people living on the shores of Lake Victoria drink and bathe in untreated water, so we used the average THg values of lake water. It was assumed that adults and children spend equal time in the water, although children are more likely to play in the water for longer periods of time than adults. THg exposure from a 30-min bath and drinking water is not high even near goldfields (Table 7). Uptake via inhalation and soil adsorbed to the skin is also minimal. In fact, the soil adherence on skin may be underestimated considerably, as conditions in East African villages and urban areas can be very dusty, and under the tropical sun a great deal of soil material can adhere to sweaty skin.

In this estimate, fish consumption accounts for the largest proportion of THg exposure to humans in East Africa. No matter how low the THg concentrations in Lake Victoria fish (Table 2), fish remains an important source of THg that should be monitored to ensure that human intake of THg remains at acceptable levels in the region. Soil geophagy (the consumption of geological materials) is practiced in traditional societies across Africa as a means to supplement micronutrient requirements, particularly by pregnant women and growing children (Smith et al., 2000). Geophagy in East Africa can take the form of prepared herbal supplements mixed with soil, consumption of termite hill soil, which provides more bioavailable nutrients, or the direct consumption of soil (Smith et al., 2000). Some pregnant women in the Jinja region drink "lake tea," a lake sediment/herbal supplement boiled in water (personal observation). Assuming that soil is directly consumed, pregnant women and children who consume an average of 28 g soil daily are estimated to ingest about 14 to 52 ng THg/kg/d,

a considerable amount, particularly for expectant mothers. However, it is unlikely the gastrointestinal tract absorbs all of the THg; much of it is in inorganic forms bound to oxyhydroxide particles. Assuming 10% absorption, the estimated exposure is 1.4 to 5.1 ng THg/kg body weight/d, still an appreciable amount compared to other routes of exposure.

All of the exposure assessments outlined above are very low in comparison to potential exposure from IHg in European-made "beauty" creams used as skin-lighteners. Harada et al. (2001) determined that European-made creams have 2.1×10^3 to 7.4×10^3 ng THg/g, 3 orders of magnitude higher than African-made creams, which have 0.18 to 2.7 ng THg/g. The creams are applied and left on skin overnight, so assuming that 1 g cream is applied each day, a person could be exposed to 8.5×10^4 ng THg/kg/d. THg exposure from African-made creams is lower, but could contribute significantly to the EDI of an adult by adding about 19.4 ng/kg/d to the total (Table 7).

Excluding soil geophagy and beauty creams, the EDIs of adults and children living away from gold fields are about 45 and 55 ng/kg/d, respectively, well below the TDI limits set out by Health Canada. The EDI of people living near gold fields are still low at 62 and 78 ng/kg/d for adults and children, respectively (Table 7). Soil geophagy may be an important route of THg for children and pregnant women, pushing their total EDIs to 59 and 114 ng/kg/d, respectively, away from gold fields and 82 and 161 ng/kg/d, respectively, near gold fields, still below the TDI limits (Table 7). However, for those who use a European-made skin-lightening cream, the cream alone is enough to exceed the TDI limits. This also presents a risk to others cohabiting with the cream users, particularly infants, because the cream residue can be transferred. In fact, one infant boy in Mwanza City was found with very high hair THg concentrations (232 ppm; Table 6), which probably was the result of such transfer as his mother also had very high hair THg concentrations (286 ppm; Harada et al., 1999).

In summary, nutritional benefits from fish consumption and soil geophagy outweigh the risks of THg poisoning for both children and adults, and should not be discouraged, even in regions near the gold fields. However, the THg concentrations in fish, water, and soil should be monitored to ensure the safety of the residents in the Lake Victoria region, because these vital resources cannot be replaced if they begin to accumulate unacceptable THg concentrations. Other routes of THg exposure (except, of course, direct handling of the Au-Hg amalgamation "sponge" and the inhalation of the air at Au-Hg amalgamation sites) do not provide appreciable amounts of THg to either children or adults. The application of European-made skin-lightening creams presents an unacceptably high risk to adults and their very young children. In agreement with Harada et al. (2001), the use of these banned creams should be better regulated in African countries. Currently, action is being taken to minimize THg exposure to gold field workers by introducing new technology amalgamation techniques and changing the shift rotations of exposed workers (DHV Consultants BV et al., 1998). It is expected that the implementation of those techniques will lead to reducing the THg risk to occupationally exposed workers.

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