



## Variation and distribution of total mercury in water, sediment and soil from northern Lake Victoria, East Africa

L.M. CAMPBELL<sup>1,4,\*</sup>, R.E. HECKY<sup>1</sup>, R. MUGGIDE<sup>2</sup>, D.G. DIXON<sup>1</sup> and P.S. RAMLAL<sup>3</sup>

<sup>1</sup>Department of Biology, University of Waterloo, Waterloo, N2L-3G1, ON, Canada; <sup>2</sup>Fisheries Resources Research Institute, P.O. Box 343, Jinja, Uganda; <sup>3</sup>Freshwater Institute, 501 University Crescent, Winnipeg, R3T 2N6, MB, Canada; <sup>4</sup>Current address: Canada Centre for Inland Waters, Burlington, ON, Canada; \*Author for correspondence (e-mail: lmcampbe@sciborg.uwaterloo.ca; phone: 905-336-6405; fax: 905-336-6430)

Received 28 May 2002; accepted in revised form 4 February 2003

**Key words:** East Africa, Lake Victoria, Mercury, Sediment cores, Soil, Water

**Abstract.** Lake Victoria, the world's largest tropical freshwater lake, is an important resource, ecologically and economically. THg distribution in the northern parts of the lake are not well known, so to answer this gap, patterns in total mercury (THg) in water, soil and two dated sediment cores from northern Lake Victoria were determined. Water THg concentrations ranged from 0.7 to 5.8 ng/L, and there were no apparent differences observed between Napoleon and Winam Gulfs. Two precipitation samples had Hg concentrations of 7 and 31 ng/L. Surface soil samples collected from various agricultural sites around Jinja, Napoleon Gulf, have THg concentrations between 12.7 and 48.4 ng/g dry weight; they were correlated with organic carbon, total phosphorus and % clay. A near-shore core taken in Itome Bay in Napoleon Gulf, and an offshore core collected from the deepest part of the lake had similar THg concentrations and profiles (78 to 458 ng/g dry weight). The increase in THg concentration in the profiles of both cores began around 1960 and peaked around 1980. The similar sedimentary THg profiles and fluxes in the cores suggest that the THg sources to L. Victoria are primarily atmospheric, with some erosion inputs, and that equatorial African ecosystems are not exempt from the global increase in baseline THg concentrations.

### Introduction

Tropical mercury (Hg) biogeochemistry in freshwater ecosystems is still a little-studied topic (Bowles et al. 2001, 2001; Ikingura and Akagi 1996), especially as most of the tropical and sub-tropical aquatic Hg studies have focused on riparian ecosystems in the Amazon Basin and wetlands in the Florida Everglades (Gilmour et al. 1998; Roulet et al. 1998a). L. Victoria, the largest tropical freshwater lake in the world by surface area (68,000 km<sup>2</sup>), supports the world's largest freshwater fishery (Pitcher and Hart 1995). Economically and environmentally, the people living in the L. Victoria basin depend on the lake and its aquatic resources. This has provided impetus for several studies focussing on Hg in environmental media in-

cluding fish, water, sediment, soil and humans mostly in the southern regions (Ikingura and Akagi 1996; van Straaten 2000). Most studies on Hg concentrations in the L. Victoria catchment has focused on the southern regions in Tanzania (see review by Campbell et al. (in press)), which has a drier savannah climate, compared to the more moist northern regions (Yin and Nicholson 2000). In all studies, THg in fish and human samples rarely exceeded marketing and health-protection limits, but THg concentrations in water and sediments were relatively high. While the knowledge of THg distribution around L. Victoria is still being improved, very little is known about THg biogeochemical cycling in tropical lakes, especially for Lake Victoria (Campbell et al. (in press)). By using original data and expanding upon published sediment core THg data (Ramlal et al. (in press)), we examine THg concentrations in water, surface soil and sediment cores collected during 1995, 1996, 1998 and 1999 in northern L. Victoria (Uganda and Kenya) and relate those to various environmental parameters. The objectives were to gain insight into THg cycling across northern L. Victoria.

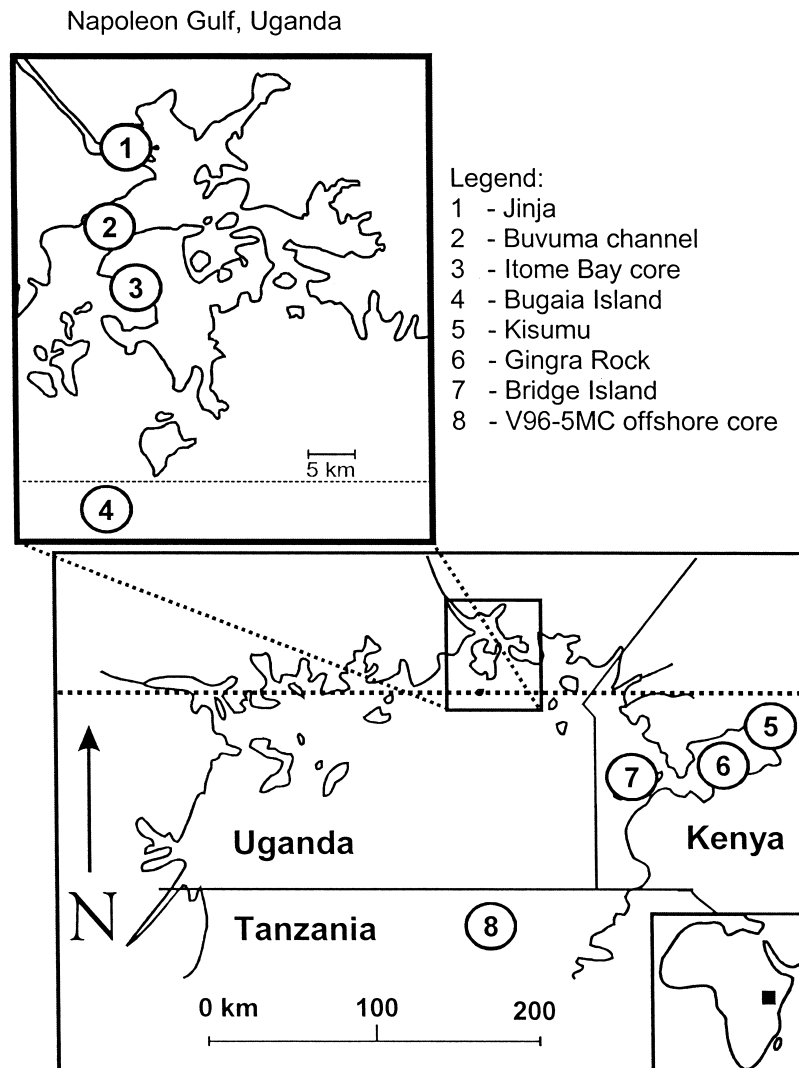
## Methods

In October–December of 1998 and 1999, unfiltered water samples for Hg analyses were collected using ultra-clean techniques from near-shore regions of Napoleon and Winam Gulfs, and two offshore sites just outside of each gulf (Table 1; Figure 1). In 1998, only two depths were sampled, surface (0.5 m) and below the thermocline. In 1999, either a depth profile was collected (Jinja, Bugaia Island and Gingra Rock) or selected depths were sampled (Buvuma, Kisumu and Bridge). Water quality parameters were measured at the site ( $O_2$ , temperature, pH) using a Hydrolab Surveyor II. Water chemistry samples were analyzed for chlorophyll-a, suspended particulate carbon (SC) and dissolved organic carbon (DOC; Table 1) at Freshwater Institute in Winnipeg, Canada following the methods of Stainton et al. (1977). Two precipitation THg samples were collected in late 1999 in Jinja by setting out a 2-L Teflon bottle topped with an acid-cleaned funnel and containing 3 mL of pure assayed HCl for immediate preservation during rain events. Immediately after the rain event, each precipitation sample was split between two 60-mL Teflon bottles for duplicate analyses. Both lake water and rain THg samples were preserved with 10 mL of assayed ultra-pure HCl, just above freezing in a refrigerator pending shipment to Canada in coolers and sent to an ultra-clean laboratory (Flett Research Ltd., 440 Desalaberry Ave., Winnipeg, Manitoba, R2L 0Y7, Canada). The analyses followed the EPA Method 1631 (U.S.E.P.A. 1999). THg was measured in all analytical reagents, including HCl, BrCl, and  $SnCl_2$  in the laboratory and HCl used to preserve the sample in field, which never exceeded more than  $0.0035 \mu\text{g/L}$ . Recovery of spiked samples averaged 86% (83–90%) with obvious but gradual decay in THg over time.

Surface soil samples were collected as a part of a stream study examining solute and solids loading into L. Victoria from 3 catchments with heavy agricultural usage

Table 1. Water and precipitation (ppt) THg concentrations (average  $\pm$  s.d., minimum and maximum) and selected water quality parameters. Note that pH values for precipitation are from September–December 1995 and the ppt THg values are from November 1999. Averages are given only for sample sizes  $> 2$ . Chl-a = chlorophyll-a, DO = dissolved oxygen, Temp = temperature, SC = suspended carbon, DOC = dissolved organic carbon. The water column profiles for THg are shown in Figure 3.

Site	Lat/Long	Date	n	THg (ng/L)		Chl-a mg/L	DO mg/L	PH	Temp °C	SC $\mu$ g/L	DOC mg/L
				min-max	avg $\pm$ s.d.						
<b>Jinja ppt</b>	00°25' N, 33°15' E	'99/'95	2	7.6-30.9	~	~	~	6.4-6.6	~	~	~
<b>Napoleon G.</b>											
Bugaia I.	04°04'11" S, 33°16'08" E	Oct '98	2	1.8-4.0	~	6.6-8.8	6.2-6.6	7.8-8.0	24.2-24.3	280-700	~
Bugaia I.	04°04'11" S, 33°16'08" E	Oct '99	6	1.4-1.8	1.6 $\pm$ 0.1	1.1-14.5	3.8-6.7	7.2-8.0	23.9-24.4	290-860	2.3-2.6
Buvuma Ch.	00°21'01" N, 33°16'69" E	Oct '99	1	0.7	~	~	~	~	~	~	~
Jinja	00°25' N, 33°15' E	Oct '98	2	3.2-5.8	~	2.3-5.5	~	6.5-8.0	25.2-25.6	760-4060	~
Jinja	00°25' N, 33°15' E	Oct '99	4	1.8-3.0	2.4 $\pm$ 0.4	4.1-5.7	0.3-3.3	7.1-7.4	24.0-24.7	450-1360	2.7-2.9
Itome Bay	00°21" N, 31° E	Oct '98	2	1.9-3.4	~	~	~	~	~	~	~
<b>Winam G.</b>											
Bridge I.	00°20'34" S, 34°06'30" E	Nov '99	2	1.2-1.2	~	1.00	2.00	7.1	24.4	~	~
Gingra R.	00°20'43" S, 34°26'40" E	Dec '98	2	2.9-3.6	~	~	7.3-8.2	7.7-8.1	26.8-27.7	~	~
Gingra R.	00°20'43" S, 34°26'40" E	Nov '99	4	1.8-2.1	2.0 $\pm$ 0.1	13.0-16.0	4.0-6.0	7.7-8.0	26.0-27.4	1980-2040	6.1-7.8
Kisumu	00°06'07" S, 34°44'35" E	Dec '98	2	3.6-4.5	~	~	7.3-7.3	7.7-7.7	26.8-27.1	~	~
Kisumu	00°06'07" S, 34°44'35" E	Nov '99	1	3.5	~	~	5.2	7.7	26.8	4450	~



*Figure 1.* Maps of northern Lake Victoria and Napoleon Gulf indicating sampling sites for soil, water and sediment cores. Sites number 5 to 7 are located in the Winam Gulf. The inset map indicates the location of Lake Victoria on the African continent. The dashed line indicates approximate location of the Equator.

in 1996 (Lindenschmidt et al. 1998). The streams are near Jinja (Figure 1), and all flow into L. Victoria. Soil types were identified according to Ollier and Harrop (1959). Grain size composition, total organic carbon (TOC), % Loss on Ignition (LOI) and total phosphorus (TP) were analyzed at the Canada Centre for Inland Waters, Environment Canada, Burlington, Ontario (Turner 1990).

In 1995, a 46-cm long core (#9511) was recovered from the deepest region of Itome Bay (Figure 1), a sheltered inshore bay of Buvuma Island, Napoleon Gulf, from a water depth of 25 m with a K.-B.<sup>®</sup> corer (Ramlal et al. (in press)). Itome Bay is often hypoxic and has consistently been a site of low fish catches (L. Campbell, personal observation). In 1996, a far-offshore 45-cm long (V96-5MC) core was recovered a depth of 68 m in an area 165 km south of Itome Bay (Figure 1), one of the deepest regions of central L. Victoria (Verschuren et al. 1998). The details on preparation and processing of core slices are discussed in Verschuren et al. (1998, 1998). Both the Itome and V96-5MC cores have been dated using the <sup>210</sup>Pb Constant Initial Concentration model (Robbins and Kemp 1978). The cores span dates from 1900 and 1840 respectively for the V96-5MC and Itome cores (Ramlal et al. (in press); Verschuren et al. 1998). The <sup>210</sup>Pb dates and sedimentation rates in this paper are as calculated by the authors (Figure 2), and Hg fluxes reported here are derived from those sedimentation rates. The V96-5MC core has a gap in its <sup>210</sup>Pb activity (Figure 2), indicating a sedimentary unconformity in the unadjusted core profiles (Verschuren et al. 1998). The adjusted <sup>210</sup>Pb dates in the V96-5MC core have been supported by patterns in diatom fossils (Verschuren et al. 2002). No sedimentary unconformity was observed in the Itome core (Ramlal et al. (in press)). The THg concentrations in each dried V96-5MC slice and soil sample were determined via atomic fluorescence spectroscopy (Ontario Ministry of Environment 1999). The dried slices from the Itome core were analyzed according to the methods of Bloom and Fitzgerald (1988). Biogenic silica (BSi) was determined spectrophotometrically after wet alkaline extraction method (DeMaster 1981), while total phosphorus (TP) was analysed following the methods of Stainton et al. (1977).

To determine the relationships between different environmental parameters and THg in water, sediment and soils, Pearson correlation analyses of the data (Zar 1984) were carried out using SYSTAT version 9.0 for Windows (SPSS Inc. 1998). When assessing water and core profiles, we assessed both unadjusted THg values and THg values normalized against total organic carbon (water TOC = SC + DOC). Since the dated core THg data constituted short time series, autocorrelation was assessed by visually examining autocorrelation function (ACF) and partial autocorrelation function (PACF) plots. First-order autocorrelation was indicated, so a first-order difference transformation was applied to all core data prior to Pearson correlation analyses.

## Results

Water THg concentrations were variable across northern L. Victoria, with the lowest concentrations found in the surface water of the Buvuma Channel (0.7 ng/L in 1999) and the highest found near Jinja in 1998 (5.8 ng/L; Table 1). Water THg concentrations are similar between Winam and Napoleon Gulfs, with higher concentrations tending to occur near towns (Jinja and Kisumu) and just below the water surface (Figure 3). THg concentrations are somewhat lower in 1999 than in 1998

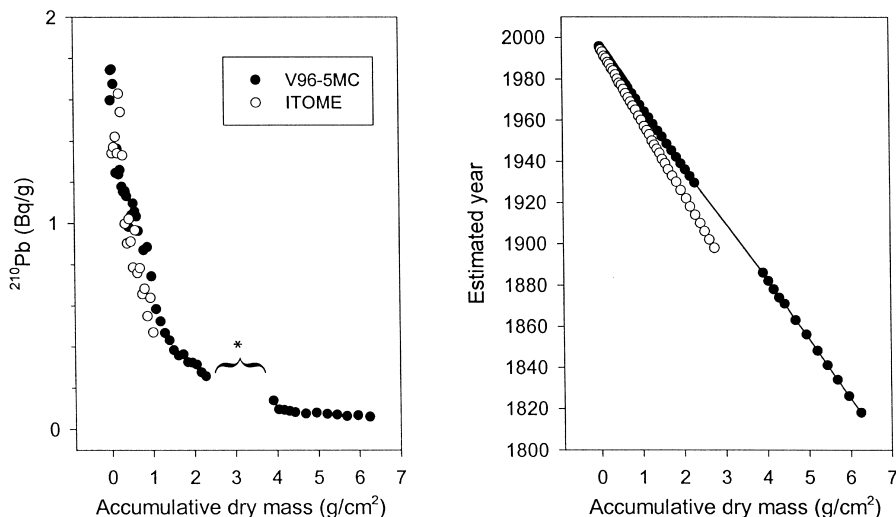


Figure 2.  $^{210}\text{Pb}$  activity and estimated dates against accumulative dry mass in the V96-5MC and Itome cores. The gap marked by asterisk in the V96-5MC core between 2.5 to 4  $\text{g}/\text{cm}^2$  indicates an unconformity thought to be the result of a lake-wide storm in the 1920's (see text).

for all locations (Table 1; Figure 3). Only chlorophyll-a was (negatively) correlated with THg concentrations near Bugaia ( $-0.660$  in 1999; Table 2). However, TOC-normalized THg concentrations are significantly correlated with oxygen concentrations and pH, as well as chlorophyll concentrations (Table 2), but note that TOC concentrations are correlated with the same parameters suggesting that TOC concentrations are influencing the correlations more than THg.

The precipitation samples showed THg concentrations of 7.6 and 30.9  $\text{ng}/\text{L}$ , somewhat higher than these seen in L. Victoria water samples (Table 1). Soil THg concentrations range between 12.7 to 48.4  $\text{ng}/\text{g}$  dry weight (Table 3). THg concentrations in soil are positively correlated with % LOI and TP, and negatively correlated with % sand (Table 4).

THg concentrations (78 to 458  $\text{ng}/\text{g}$  dw) and  $\text{THg}_{\text{norm}}$  concentrations (0.5 to 2.0  $\text{ng}$  THg/mg TOC) in the Itome and V96-5MC cores follow very similar trends and are higher than those in soil (Figure 4, Table 5). THg fluxes in both cores are also similar, with maximum flux peaking at 8–13  $\text{ng}/\text{cm}^2/\text{yr}$  between 1960 and 1980 (Table 5). BSi concentrations in the V96-5MC core are an order of magnitude higher than those in the Itome core. TP patterns differ, as there is a sharp decline in TP concentrations from 2.1  $\text{mg}/\text{g}$  to 0.5  $\text{mg}/\text{g}$  with depth in the V96-5MC core, but there is a more gradual decline from 1.8 to 1.1  $\text{mg}/\text{g}$  with depth in the Itome core (Figure 5). The TOC concentrations are similar in both cores, with a more pronounced dip between 1940 and 1980 in the Itome core (Table 5, Figure 5). The sediment accumulation (0.03  $\text{g}/\text{cm}^2/\text{yr}$ ) and THg flux (5.5  $\text{ng}/\text{cm}^2/\text{yr}$ ) are similar for both cores (Table 5). After correcting for autocorrelation, THg concentrations are significantly correlated with %LOI, TP and BSi in V96-5MC offshore core

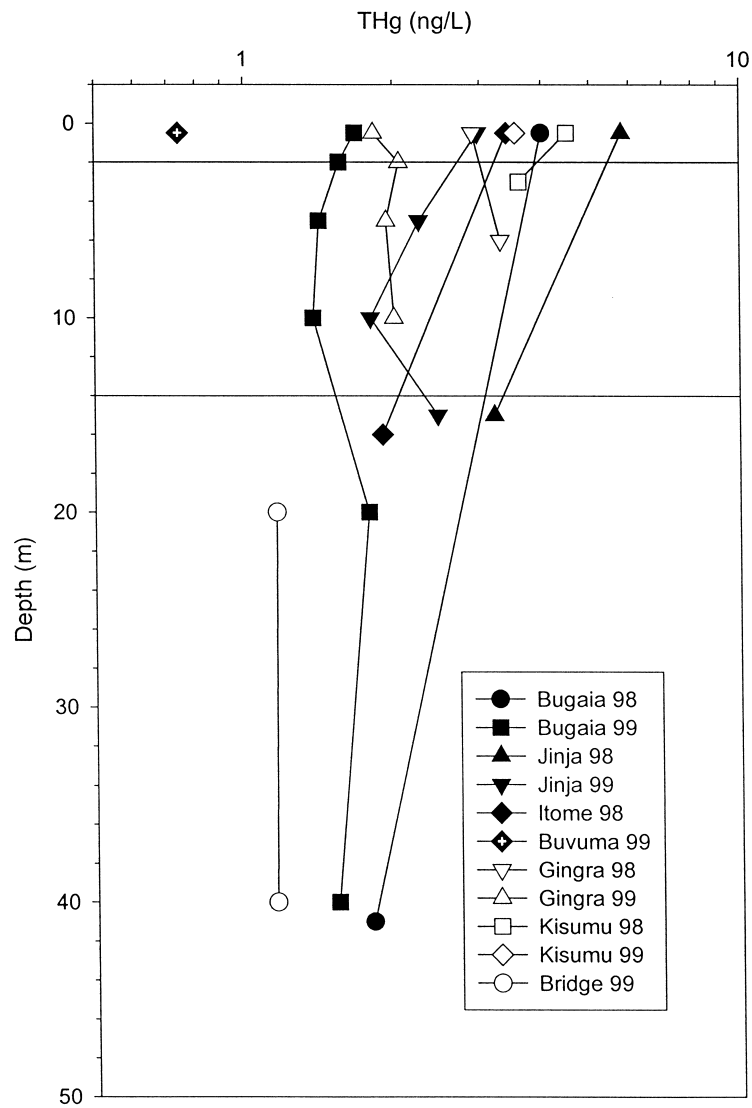


Figure 3. Water depth profiles for THg for the 7 sites in Napoleon and Winam Gulfs sampled in 1998 and 1999. The horizontal bars indicate the average depths where the oxyclines and thermoclines have been measured, with the top bar for shallow sites (< 10 m) and the bottom bar for deeper sites (> 10 m).

(Table 6). In the near-shore Itome core, THg is not correlated with BSi but is positively correlated with TP and TOC (Table 7).

Table 2. Correlation matrix for Bugaia Island water samples collected in 1999. Bold values indicate significance at  $p < 0.10$  ( $n = 6$ ). Normalized THg (Norm. THg) is the THg concentrations normalized against TOC concentrations. TOC is the sum of DOC and SC values (mg/L; see Table 1). Other acronyms are as defined in Table 1.

	THg	Norm. THg	TOC	DO	pH	Temp
Norm. THg	<b>-0.815</b>	~	~			
TOC	-0.276	<b>-0.780</b>	~			
Oxygen	-0.154	<b>-0.684</b>	<b>0.958</b>	~		
pH	-0.167	<b>-0.669</b>	<b>0.910</b>	<b>0.979</b>	~	
Temperature	-0.008	-0.565	<b>0.917</b>	<b>0.959</b>	<b>0.968</b>	~
Chl-a	<b>-0.660</b>	<b>-0.867</b>	<b>0.717</b>	<b>0.731</b>	<b>0.692</b>	0.527

## Discussion

Water THg concentrations, 0.7 to 4.0 ng/L, in northern L. Victoria are high compared to the temperate great lakes Baikal, Ontario and Superior which have THg concentrations ranging from 0.1 to 1.0 ng/L (Amyot et al. 2000; Mason and Sullivan 1997; Meuleman et al. 1995). The relatively uniform water THg concentrations across northern L. Victoria and the similar deposition rates in cores suggest a well-mixed and spatially uniform input, perhaps from atmospheric sources. THg concentrations in Winam Gulf support this view. Although its waters do not mix with the main lake (Figure 1), and although there is urbanization around Kisumu and intense agricultural activity on the gulf, its THg concentrations are similar to these in the open well-mixed Napoleon Gulf. THg concentrations usually are higher near the surface than in deeper waters (Figure 3). THg concentrations are consistently elevated immediately near the cities of Jinja and Kisumu, where untreated sewage effluents are common in these shallow nearshore environments (Campbell et al. (in press)).

THg concentrations were correlated with chlorophyll in offshore Bugaia waters, while TOC-normalized THg concentrations were correlated with oxygen and pH as well as chlorophyll. These correlations down the water column are the result of the thermal stratification at this deep station (Figure 3) which also stratified other water column properties because of production processes in the surface layer and regeneration in the deeper layers (Hecky and Bugenyi 1992). This suggests that THg concentrations in water are strongly impacted by physical and chemical processes that also influence phytoplankton growth and there may be a link between phytoplankton abundance and THg biogeochemical cycles in offshore L. Victoria.

Precipitation THg concentrations were 7 and 31 ng/L in late 1999. The 31 ng/L sample was from a brief but intense precipitation event (about half hour in duration), while the 7 ng/L sample was from an overnight precipitation event. This seems to point to a "scrubbing" event where a fixed amount of atmospheric Hg is diluted by the volume of wet precipitation. In tropical regions of the Pacific and Atlantic Oceans wet precipitation THg concentrations ranged between 2.0 to 20



Table 3. Mercury concentrations in different soil samples from streams near Jinja (00°25' N, 33°15' E), Napoleon Gulf. Soil types and landscape uses are indicated. (1) Nakobango catena – dark red fertile clay. (2) Kifu series – alluvial gray fine-grained sands formed from hill wash. (3) Kyebe catena – red gravelly loam. (A) = subsidence farming, (B) = wetlands downstream from sugar cane plantation, (C) = near town, (D) = next to a road.

Stream	Station	THg (ng/g dw)	TOC (mg/g)	% Gravel	% Sand	% Silt	% Clay	TP (µg/g)	% LOI	Soil type	Land use
Kagonja	1a	41.6	1.6	0.0	3.5	28.5	68.0	464.6	5.9	1	A, C
Kagonja outlet	2 – top	46.0	6.8	0.0	5.2	32.2	62.7	862.4	11.3	2	B
Kagonja outlet	2 – bank	30.5	1.2	0.0	10.2	8.5	81.3	312.0	4.1	2	B
Kagonja outlet	2 – bottom	48.4	1.6	0.0	4.3	34.6	61.1	899.6	12.8	2	B
Bugungu	3 – road	12.7	1.2	6.2	41.5	14.7	37.6	290.8	2.5	2, next to	A, D
Bugungu	3 – field	29.5	0.9	0.0	9.1	40.6	50.3	109.9	2.7	3	A, D
Bugungu – outlet	4 – field	29.7	3.7	0.0	8.8	10.9	80.3	432.8	5.9	2	A, D
Kibale	6 – bank	44.5	10.7	0.0	4.4	8.8	86.8	506.4	11.4	2	A
Kabale	6 – field	23.1	5.9	0.0	4.4	8.8	86.8	209.3	5.6	2	A

Table 4. Correlation matrix for soil parameters. Bold values indicate significance at  $p < 0.10$  ( $n = 9$ ).

	THg	TOC	% Sand	% Silt	% Clay	TP
TOC	0.354	~				
% Sand	<b>-0.739</b>	-0.359	~			
% Silt	0.423	-0.362	-0.200	~		
% Clay	0.279	<b>0.565</b>	<b>-0.668</b>	<b>-0.595</b>	~	
TP	<b>0.777</b>	0.251	-0.318	0.330	0.001	~
% LOI	<b>0.846</b>	<b>0.579</b>	<b>-0.532</b>	0.181	0.288	<b>0.884</b>

ng/L (Lamborg et al. 1999). In a forested Amazon catchment, precipitation values ranged from 4 to 23 ng/L (mean, 9.2 ng/L) (Fostier et al. 2000). In Minnesota and Quebec, THg concentrations ranged from 0.8 to 19.5 ng/L (Glass and Sorensen 1999; Poissant and Pilote 1998). It is not known why one sample (31 ng/L) would exceed those values especially as the L. Victoria catchment is not highly industrialized, and, as such, this deserves further investigation. It would seem that a potential prevailing source of atmospheric THg in the region would be biomass burnings, which can be an important global source of atmospheric mercury (Freidli et al. 2001), and gaseous Hg from biomass burnings has been measured in Africa (Baker et al. 2002; Brunke et al. 2001). Remote sensing and atmospheric monitoring studies have determined that Africa constitutes a high proportion of global biomass burnings and biomass burning emissions from Africa likely exert significant influences upon local and global atmospheric chemistry (Dwyer et al. 2000; Scoholes and Andreae 2000). Excessive unregulated biomass burnings and anthropogenic land impacts still continue in the L. Victoria basin, and are now recognized as an emerging environmental issue for the lake (The Republic of Uganda 1999).

It is interesting to note that THg in Jinja soils are correlated with TP, suggesting that oxyhydroxides may play a role in retaining THg. While Al and Fe oxyhydroxides were not measured for the soil samples, it is known that in Uganda (Reedman 1984) and other regions of Africa (Karim and Adams 1984), higher Fe- and Al-oxyhydroxide content in soils are usually associated with increasing clay content and are correlated with phosphorous. In addition, the red nitisols (ferrisols) around Jinja has high Fe and clay content (Table 3), supporting the hypothesis that the correlation between THg and TP indicates an association with oxyhydroxides. For example, in Tanzania near Mwanza Gulf, soil samples collected near Au-Hg processing sites have shown extremely elevated THg concentrations (250 to 1560 ng/g), although the THg concentrations declined very quickly ( $\sim 12$  ng THg/g) with depth in the soil cores and at a distance from the processing sites (van Straaten 2000). This rapid decline was attributed to the presence of oxyhydroxides in the Tanzanian soils restricting Hg movement away from the Hg source (van Straaten 2000). Also in the Amazon, extensive geochemistry studies have indicated that THg concentrations are correlated with extracted Al and Fe from oxyhydroxides (Roulet et al. 1998b). A review of forested soils from around the world (Roulet et al. 1998b) indicates that the Jinja surface soil THg concentrations (13–48 ng/g) fall within the ranges for

Table 5. Average  $\pm$  s.d., minimum and maximum parameters in cores and number of slices analyzed for near-shore Itome and offshore Y96-5MC cores.  $\text{THg}_{\text{norm}}$  are  $\text{THg}$  concentrations normalized against total organic carbon (TOC) in each slice.

Site	Long/Lat & Date	n		avg s.d.	min-max
Itome Bay	00°21' N 31° E 09-Oct-1995	25	$\text{THg}$ (ng/g dw)	$191.4 \pm 64.1$	88.0–310.0
		23	$\text{THg}_{\text{norm}}$ (ng $\text{THg}$ /mg TOC)	$1.1 \pm 0.3$	0.6–1.7
		25	Biogenic Si (mg/g)	$6.2 \pm 2.3$	3.6–12.5
		25	Phosphorus (mg/g)	$1.4 \pm 0.2$	1.1–1.8
		25	TOC (mg/g)	$184.2 \pm 25.7$	129.0–219.0
Y96-5MC	01°13.9' S 33°11.8' E 22-May-1996	~	Water $\text{O}_2$ at 25 m (mg/L)	1.0	~
		25	Sedimentation rate ( $\text{g}/\text{cm}^2/\text{yr}$ )	0.0276	(constant)
		25	$\text{THg}$ flux ( $\text{ng}/\text{cm}^2/\text{yr}$ )	$5.46 \pm 1.16$	2.43–7.93
		31	$\text{THg}$ (ng/g dw)	$190.1 \pm 92.4$	77.9–458.1
		20	$\text{THg}_{\text{norm}}$ (ng $\text{THg}$ /mg TOC)	$0.9 \pm 0.3$	0.5–2.0
		31	Biogenic Si (mg/g)	$85.7 \pm 25.4$	42.2–124.0
		19	Phosphorus (mg/g)	$0.9 \pm 0.6$	0.5–2.1
		20	TOC (mg/g)	$203.7 \pm 4.6$	198.1–211.5
		31	% LOI	$60.2 \pm 1.1$	57.6–61.3
		~	Water $\text{O}_2$ at 68 m (mg/L)	< 0.1	~
		31	Sedimentation rate ( $\text{g}/\text{cm}^2/\text{yr}$ )	$0.032 \pm 0.001$	0.029–0.033
		28	$\text{THg}$ flux ( $\text{ng}/\text{cm}^2/\text{yr}$ )	$5.52 \pm 2.51$	2.32–13.8

Table 6. Correlation matrix for V96-5MC offshore core parameters. Coefficient values have been corrected for autocorrelation (first order of difference). BSi = biogenic silica, TOC = total organic matter, LOI = loss on ignition, TP = total phosphorous. Bold values indicate significance at  $p < 0.05$  ( $n = 31$ ).

	THg	BSi	TOC	TP
BSi	<b>0.371</b>	~		
TOC	0.293	<b>0.395</b>	~	
TP	<b>0.351</b>	0.093	<b>0.856</b>	~
% LOI	<b>0.495</b>	<b>0.389</b>	<b>0.935</b>	<b>0.926</b>

Table 7. Correlation matrix for the Itome near-shore core parameters. Bold values indicate significance at  $p < 0.05$  ( $n = 25$ ).

	THg	BSi	TOC
BSi	0.242	~	
TOC	<b>0.547</b>	<b>0.700</b>	~
TP	<b>0.412</b>	<b>0.686</b>	<b>0.456</b>

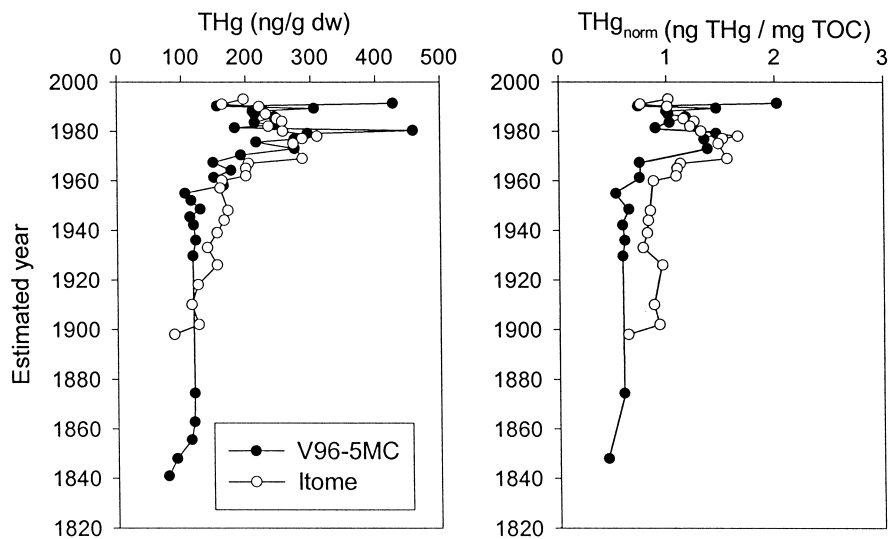


Figure 4. THg (ng/g dw) and normalized THg (ng THg/mg TOC) core profiles for the far-offshore V96-5MC core and the near-shore Itome core.

temperate soils in North America and Sweden (1–325 ng/g), but are lower than for the Amazon soils (60–219 ng/g). Data on "normal" THg concentrations in African soils are very limited and clearly indicates a need to survey soil concentrations across East Africa.

THg concentrations (78–458 ng/g), normalized THg concentrations (0.5–2.0 ng THg/mg TOC) and fluxes (2.3–13.8 ng/cm<sup>2</sup>/yr) in the two sediment cores from Itome Bay and central L. Victoria were remarkably similar and followed similar

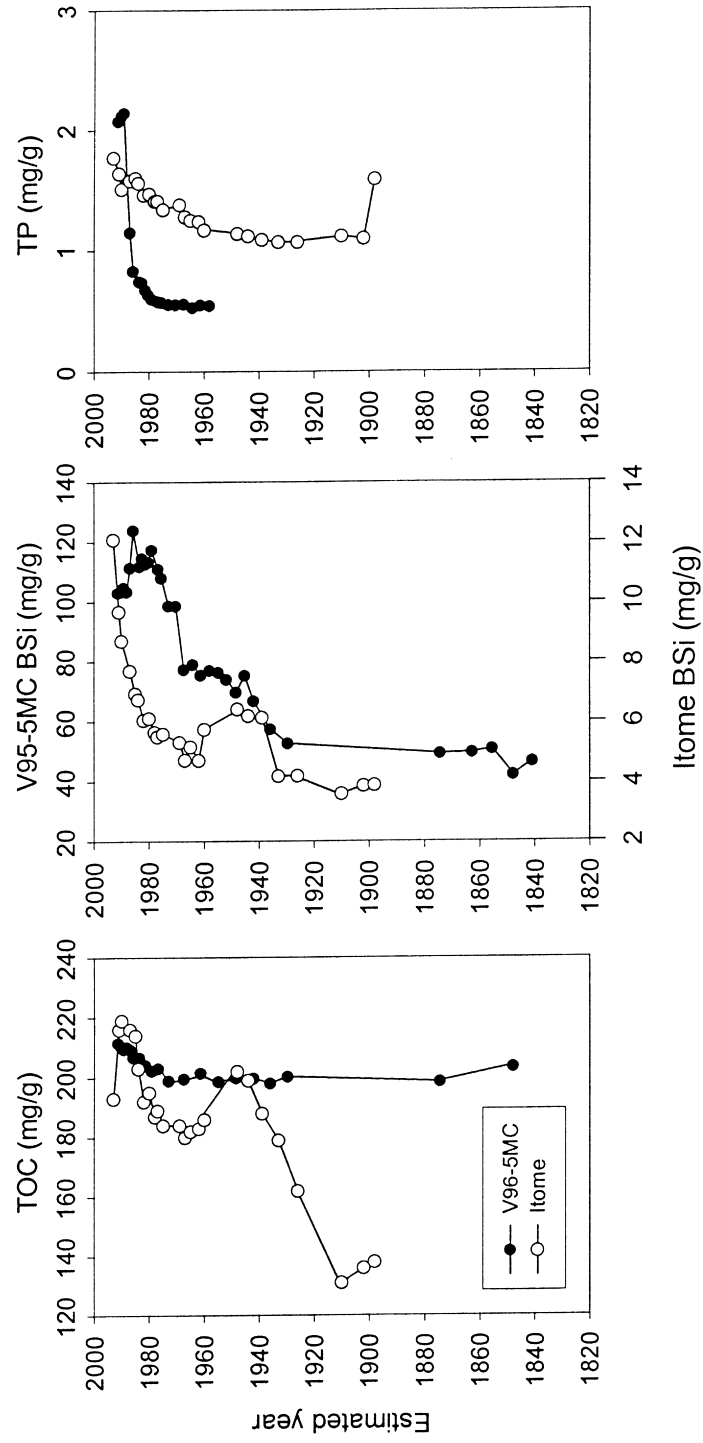


Figure 5. The nutrient profiles for BSi, TOC, and TP concentrations for the far-offshore V96-5MC core and the near-shore Itome core. Note that BSi concentrations in the V96-5MC core are an order of magnitude higher than in the Itome core, and that different scales are shown for each core.

trends in dated sediments despite the large distance between the two coring sites and the difference in sampling depths. The lack of consistent spatial relationships with TP and BSi suggests that THg chemistry in L. Victoria may be independent of phosphorous and diatomic patterns. The similarity in TOC-normalized THg concentrations between the two sites and the consistent correlation with TOC supports the assumption that Hg diagenesis will be similar at both sites and that TOC is an important factor in THg cycling in sediments. L. Victoria sediments are rich in organic material (Hecky 1993), which provides a good binding substrate for Hg (Meili 1997). The L. Victoria THg concentrations are similar to the ranges found for THg measured in the sediment of Lakes Michigan and Superior (30–380 and 94–160 ng/g respectively; Mudroch et al. (1988)). However, the L. Victoria concentrations are lower than for Lakes Ontario and Erie with values between 140 to 4800 ng/g (Mudroch et al. 1988). A study in southern L. Victoria found that wetland sediments near gold mines had elevated THg concentrations of 170–5350 ng/g dw prior to entering the Igonozela wetlands, while wetland sediments collected near Mwanza Gulf had very low THg concentrations (10–20 ng/g dw; van Straaten (2000)). The higher THg concentrations in northern L. Victoria relative to low concentrations in sediments from the southern regions suggest important sources of THg other than liquid Hg used in gold-ore processing.

An anthropogenic effect on Hg mobilization from the catchment of L. Victoria could be reasonably expected. Anthropogenic THg sources likely increased when agricultural and developmental activities escalated in the African Great Lakes region after World War II (1945) with population growth at rates exceeding 3% per year in sub-Saharan Africa into the 1990's (Hecky and Bugenyi 1992). This is reflected in the increase in baseline THg concentrations in both cores after 1920–40's (Figure 4). Anthropogenic influences in the L. Victoria basin has already been implicated in excessive nutrient (C, N, P) inputs, significant shifts in diatom and chironomid species, increased concentrations of polyaromatic hydrocarbons from wood and fuel combustion, and the introduction of persistent organic pollutants (DDT, toxaphene) in recent short cores (Hecky 1993; Lipiatou et al. 1996; Verschuren et al. 2002). Similar anthropogenic-related increases in THg concentrations in cores from various lakes across North America and Europe have been detected, with the peak THg starting in the mid-19th century in the USA and a little later in Canada and the Scandinavia (Fitzgerald et al. 1998). In a study comparing pre-industrial and recent flux for various lakes across northern latitudes, the Hg core flux ratios ranged from 0.7 to 8.9, with the mean values lying between 1 and 5 (Landers et al. 1998). Similarly, the ratios of THg flux from pre-industrial ( $\leq 1910$ ) and recent sediments ( $\geq 1969$ ) are 2.43 for the Itome core and 2.46 for the V96-5MC core. The increasing flux ratios reflect a global increase in baseline Hg concentrations since the industrial revolution, and it appears that tropical freshwater systems may not be exempt from this global increase.

In the L. Victoria basin, there are two possible explanations for the rise and decline of THg concentrations seen in both cores. In the first scenario, the rate of sedimentation has remained similar over the years, so the atmospheric deposition of Hg has actually risen and fallen over time. Under this scenario, Hg concentra-

tions in L. Victoria are presently dropping from higher values, which started to rise around 1960 and reached a maximum sometime between 1970 and the early 1980's. In the second scenario, the rate of sedimentation may have been increasing since 1980's, "diluting" Hg concentrations in recent sediments. This means that THg input to the lake has remained the same, or may even be increasing, over the last two decades. The constant sedimentation rates calculated for both the Itome and V96-5MC cores (Figure 2) and the lower THg concentrations in 1999 water samples compared to these collected in 1998 (Table 1; Figure 3) seem to support the first hypothesis, providing positive news that Hg concentrations are declining in L. Victoria. However, the recent eutrophication of L. Victoria and possibly increased erosion due to the expanding population density seems to support the second hypothesis, especially as BSi and TP concentrations have been increasing in younger sediments (Figure 5). Further paleolimnological studies and further water collections are planned to ascertain Hg fluxes and sedimentation rates across L. Victoria and to confirm the apparent decline of Hg fluxes to the lake.

### Acknowledgements

The staff and scientists at the Fisheries Research Institute, the European Union Lake Victoria Fisheries Research Project (both in Jinja, Uganda) and the Kenya Marine Fisheries Research Institute (Kisumu, Kenya) helped to co-ordinate the sampling trips and provided laboratory and storage space. Dr Greg Mierle (Dorset Environmental Research Centre, Ontario Ministry of Environment) lent laboratory space and the use of Hg analysis equipment. Xiaowa Wang (Canada Centre for Inland Waters, Environment Canada, Burlington, ON) analyzed the nutrient and grain size of the sediment and soil samples. Dr Dirk Verschuren (University of Ghent) discussed sampling protocols, dating methodology and paleolimnological interpretations for the V96-5MC cores. Paul Wilkinson provided details of the  $^{210}\text{Pb}$  dating for the Itome core. Financial support was provided by International Development Research Council Doctorate Awards to LMC and NSERC research grants to REH and DGD.

### References

- Amyot M., Lean D.R.S., Poissant L. and Doyon M.-R. 2000. Distribution and transformation of elemental mercury in the St. Lawrence River and Lake Ontario. *Can. J. Fish. Aquat. Sci.* 51, (Suppl.1): 155–163.
- Baker P.G.L., Brunke E.-G., Slemr F. and Crouch A.M. 2002. Atmospheric mercury measurements at Cape Point, South Africa. *Atmos. Environ.* 36: 2459–2465.
- Bloom N.S. and Fitzgerald W. 1988. Determination of volatile mercury species at the picogram level by low temperature gas chromatography with cold-vapour atomic fluorescence detection. *Anal. Chim. Acta.* 208: 151–161.

- Bowles K.C., Apte S.C., Maher W.A., Kawei M. and Smith R. 2001. Bioaccumulation and biomagnification of mercury in Lake Murray, Papua New Guinea. *Can. J. Fish. Aquat. Sci.* 58: 888–897.
- Brunke E.G., Labuschagne C. and Slemr F. 2001. Gaseous mercury emissions from a fire in the Cape Peninsula, South Africa during January 2000. *Geophys. Res. Lett.* 28: 1483–1486.
- Campbell L.M., Hecky R.E. and Dixon D.G. Review of mercury in Lake Victoria (East Africa): Implications for human and ecosystem health. *Journal of Toxicology and Environmental Health, Part B*, In press-a (in press).
- Campbell L.M., Hecky R.E., Nyaundi J., Muggide R. and Dixon D.G. Distribution and food-web transfer of mercury in Napoleon and Winam Gulfs, Lake Victoria, East Africa. *J. Great Lakes Res.*, In press-b (in press).
- DeMaster D.J. 1981. The supply and accumulation of silica in the marine environment. *Geochim. Cosmochim. Acta.* 45: 1715–1732.
- Dwyer E., Pinnock S., Grégoire J.-M. and Pereira J.M.C. 2000. Global spatial and temporal distribution of vegetation fire as determined from satellite observations. *Int. J. Remote Sensing* 21: 1289–1302.
- Fitzgerald W.F., Engstrom D.R., Mason R.P. and Nater E.A. 1998. The case for atmospheric mercury contamination in remote areas. *Environ. Sci. Technol.* 32: 1–7.
- Fostier A.-H., Forti M.C., Guimarães J.R.D., Melfi A.J., Boulet R., Espirito Santo C.M. et al. 2000. Mercury fluxes in a natural forested Amazonian catchment (Serra do Navio, Amapá State, Brazil). *Sci. Tot. Environ.* 260: 201–211.
- Freidli H.R., Radke L.F. and Lu J.Y. 2001. Mercury in smoke from biomass fires. *Geophysical Research Lett.* 28: 3223–3226.
- Gilmour C.G., Riedel G.S., Ederington M.C., Bell J.T., Benoit J.M., Gill G.A. et al. 1998. Methylmercury concentrations and production rates across a trophic gradient in the northern Everglades. *Biogeochemistry* 40: 327–345.
- Glass G.E. and Sorensen J.A. 1999. Six-year trend (1990–1995) of wet mercury deposition in the upper midwest, USA. *Environ. Sci. Technol.* 33: 3303–3312.
- Hecky R.E. 1993. The eutrophication of Lake Victoria. *Verh. Internat. Verein. Limnol.* 25: 39–48.
- Hecky R.E. and Bugenyi F.W.B. 1992. II. Water Quality: Hydrology and chemistry of the African Great Lakes and water quality issues: Problems and solutions. *Mitt. Internat. Verein. Limnol.* 23: 45–54.
- Ikingura J.R. and Akagi H. 1996. Monitoring of fish and human exposure to mercury due to gold mining in the Lake Victoria goldfields, Tanzania. *Sci. Tot. Environ.* 191: 59–68.
- Karim M.I. and Adams W.A. 1984. Relationships between sesquioxides, kaolinite and phosphate sorption in a catena of oxisols in Malawi. *Soil Sci. Soc. Am. J.* 48: 406–409.
- Lamborg C.H., Rolfhus K.R., Fitzgerald W.F. and Kim G. 1999. The atmospheric cycling and air-sea exchange of mercury species in south and equatorial Atlantic Ocean. *Deep-Sea Research Part II – Topical Studies in Oceanography* 46: 957–977.
- Landers D.H., Gubala C., Verta M., Lucotte M., Johansson K., Vlasova T. et al. 1998. Using lake sediment mercury flux ratios to evaluate the regional and continental dimensions of mercury deposition in Arctic and boreal ecosystems. *Atmos. Environ.* 32: 9119–9928.
- Lindenschmidt K.-E., Suhr M., Magumba M.K., Hecky R.E. and Bugenyi F.W.B. 1998. Loading of solute and suspended solids from rural catchment areas flowing into Lake Victoria in Uganda. *Wat. Res.* 32: 2776–2786.
- Lipiatou E., Hecky R.E., Eisenreich S.J., Lockhart L., Muir D. and Wilkinson P. 1996. Recent ecosystem changes in Lake Victoria reflected in sedimentary natural and anthropogenic organic compounds. In: Johnson T.C. and Odada E.O. (eds), *The Limnology, Climatology, and Paleoclimatology of the East African Lakes*. Gordon and Breach Publishers, Amsterdam, The Netherlands, pp. 523–541.
- Mason R.P. and Sullivan K.A. 1997. Mercury in Lake Michigan. *Environ. Sci. Technol.* 31: 942–947.
- Meili M. 1997. Mercury in Lakes and Rivers. *Metal Ions in Biological Systems* 34: 21–51.
- Meuleman C., Leermakers M. and Baeyens W. 1995. Mercury speciation in Lake Baikal. *Water Air Soil Pollut.* 80: 539–551.
- Mudroch A., Sarazin L. and Lomas T. 1988. Summary of surface and background concentrations of selected elements in the Great Lakes sediments. *J. Great Lakes Res.* 14: 241–251.



- Ollier C.D. and Harrop J.F. 1959. The Soils of the Eastern Province of Uganda: Memoirs of the Research Division, Series 1. Department of Agriculture, Uganda Protectorate (currently available from the Kawanda Agriculture Research Institute, National Agricultural Research Organization, Kawanda, Uganda), Kawanda, Uganda, No. 2. pp.
- Ontario Ministry of Environment 1999. Automated Determination of Total Mercury at Ultratrace Levels in Environmental Samples. Laboratory Services Branch, Ontario Ministry of Environment, Toronto.
- Pitcher T.J. and Hart P.J.B. (eds) 1995. The Impact of Species Changes in African Lakes. Chapman & Hall, London, Great Britain, 601 pp.
- Poissant L. and Pilote M. 1998. Mercury concentrations in single event precipitation in southern Québec. *Sci. Tot. Environ.* 213: 65–72.
- Ramlal P.S., Bugenyi F.W.B., Kling G.W., Nriagu J.O., Rudd J.W.M. and Campbell L.M. Lake Victoria, East Africa: Mercury concentrations in water, sediment, and biota. *J. Great Lakes Res.*, In press (in press).
- Reedman J.H. 1984. Resources of phosphate, niobium, iron, and other elements in residual soils over the Sukulu Carbonatite Complex, southeastern Uganda. *Economic Geology* 79: 716–724.
- Robbins J.A. and Kemp A.L.W. 1978. Comparative <sup>210</sup>Pb, <sup>137</sup>Cs, and pollen geochronologies of sediments from lakes Ontario and Erie. *Quaternary Res.* 10: 256–278.
- Roulet M., Lucotte M., Canuel R., Rheault I., Tran S., De Freitas Gog Y.G. et al. 1998a. Distribution and partition of total mercury in waters of the Tapajós River Basin, Brazilian Amazon. *Sci. Tot. Environ.* 213: 203–211.
- Roulet M., Lucotte M., Saint-Aubin A., Tran S., Rhéault I., Farella N. et al. 1998b. The geochemistry of mercury in central Amazonian soils developed on the Alter-do-Chão formation of the lower Tapajós River Valley, Pará state, Brazil. *Sci. Tot. Environ.* 223: 1–24.
- Scholes M. and Andreae M.O. 2000. Biogenic and pyrogenic emissions from Africa and their impact on the global atmosphere. *Ambio.* 29: 23–29.
- SPSS Inc. 1998. SYSTAT Version 10. Computer Statistical Software.
- Stainton M.P., Capel M.J. and Armstrong F. 1977. The Chemical Analysis of Fresh Water. Freshwater Institute, Canadian Fisheries and Marine Service Spec. Publication, Winnipeg, MB, Canada.
- The Republic of Uganda 1999. State of the Environment Report for Uganda 1998. ISBN 9970 410 014. National Environmental Management Authority, Kampala, Uganda.
- Turner L.J. 1990. CCIW Laboratory Manual for the Determination of Metals, Total Iron, Phosphorus, Carbon, Sulfur and Mossbauer Analyses of Sediment and Suspended Sediment Samples. Canada Centre for Inland Waters, Burlington, Ontario, Canada.
- U.S.E.P.A. 1999. Method 1631, Revision B. Mercury in Water by Oxidation, Purge and Trap, and Cold Vapor Atomic Fluorescence Spectrometry. United States Environmental Protection Agency, Office of Water 4303. Report No. EPA-821-R-99-005., Also found at <http://www.epa.gov/ost/methods/1631method.html>.
- van Straaten P. 2000. Mercury contamination associated with small scale gold mining in Tanzania and Zimbabwe. *Sci. Tot. Environ.* 259: 105–113.
- Verschuren D., Edgington D.N., Kling H.J. and Johnson T.C. 1998. Silica depletion in Lake Victoria: sedimentary signals at offshore stations. *J. Great Lakes Res.* 24: 118–130.
- Verschuren D., Johnson T.C., Kling H.J., Edgington D.N., Leavitt P.R., Brown E.T. et al. 2002. History and timing of human impact on Lake Victoria, East Africa. *Proceedings B of The Royal Society of London* 269: 289–294.
- Yin X. and Nicholson S.E. 2000. On the diurnal cycle of cloudiness over Lake Victoria and its influence on evaporation from the lake. *Hydrol. Sci.* 45: 407–424.
- Zar J.H. 1984. Biostatistical Analysis. Simon & Schuster Co., Eaglewoods Cliffs, New Jersey, USA, 718 pp.