J. Great Lakes Res. 29 (Supplement 2):267–282
Internat. Assoc. Great Lakes Res., 2003

Distribution and Food-web Transfer of Mercury in Napoleon and Winam Gulfs, Lake Victoria, East Africa

Linda M. Campbell[1,*], Robert E. Hecky[1], Joseph Nyaundi[2], Rose Muggide[3], and D. George Dixon[1]

[1]*Department of Biology*
University of Waterloo
200 University Avenue West
Waterloo, Ontario N2L-3G1

[2]*Kenya Marine Fisheries Research Institute*
P. O. Box 1881
Kisumu, Kenya

[3]*Fisheries Resources Research Institute*
P.O. Box 343
Jinja, Uganda

ABSTRACT. *Mercury (Hg) concentrations were measured for the food webs and water of Napoleon Gulf (Uganda) and Winam Gulf (Kenya) in northern Lake Victoria. Water total mercury (THg) concentrations in Lake Victoria range from 1.7 to 5.8 ng/L, while methylmercury (MeHg) concentrations range from 0.2 to 1 ng/L. Water Hg concentrations in Lake Victoria are higher than in temperate great lakes, including Lakes Baikal, Michigan, and Ontario, but the top predator Nile perch have relatively low THg concentrations compared to temperate piscivorous fish. While the water Hg concentrations are similar between Napoleon and Winam gulfs, the THg concentrations in biota are significantly higher in Napoleon Gulf than in the same species from Winam Gulf, which may be due to biogeochemical differences in each gulf. THg concentrations in Nile perch and Nile tilapia consistently increase with total length in both gulfs and the rates of increase are similar. The rates of THg bioaccumulation, as indicated by the regression slopes of log-THg vs. stable nitrogen isotope values for each food web (slopes of 0.163 and 0.165 for Napoleon and Winam gulfs, respectively), are within the ranges of bioaccumulation rates observed in temperate and tropical lakes elsewhere which suggests that Hg bioaccumulates at a similar rate in diverse aquatic food webs, regardless of latitude or species composition.*

INDEX WORDS: *Mercury, food webs, stable nitrogen isotopes, water, Lake Victoria.*

INTRODUCTION

Methylmercury (MeHg), a potent neurotoxic chemical, is known to biomagnify through food webs, and can reach concentrations 10^6 times higher in top predator fish than in either their ambient environment or diet (Fitzgerald *et al.* 1998). Since total Hg (THg) in fish can be more than 90% MeHg (Bloom 1992), this represents a serious human health concern where fish and fishing industries are particularly important, such as Lake Victoria in East Africa. L. Victoria is the largest tropical freshwater lake (68,000 km^2) in the world, and supports the world's largest freshwater fishery (Pitcher and Hart 1995). The lake is relatively shallow with a maximum depth of 69 meters (Johnson *et al.* 2000). The lake receives nearly 80% of its water inputs from rain directly to the surface; a similar amount is lost to evaporation (Bootsma and Hecky 1993). Since the water in the lake has a turnover time of 23 years, there is ample opportunity for nonvolatile contaminants to concentrate in the water and sediments of the system (Bootsma and Hecky 1993). People living in the L. Victoria region support themselves by fishing and agriculture (Geheb and Binns 1997), activities that lead to in-

*Corresponding author. E-mail: linda.campbell@ec.gc.ca
Current address: Canada Centre for Inland Waters, Environment Canada, 867 Lakeshore Road, Burlington, Ontario L7R 4A6

creased environmental pressures on the lake, including overfishing, declining biodiversity, eutrophication and deep water anoxia (Bootsma and Hecky 1993, Hecky 1993, Hecky *et al.* 1994, Kaufman 1992, Ogutu-Ohwayo 1990).

Food web studies have benefited by the introduction of stable isotope analyses (Peterson and Fry 1987). Even in complex ecosystems, such as Lake Victoria with an estimated 288 fish species (Pitcher and Hart 1995), stable isotope ratios make it possible to numerically characterize food web structure and to determine contaminant bioaccumulation patterns. The ratio of ^{15}N to ^{14}N ($\delta^{15}N$) in tissue typically increases consistently with trophic transfers because ^{15}N is retained from the food resource relative to ^{14}N, so ^{15}N is enriched in the consumer by approximately 3 to 4‰ (Vander Zanden and Rasmussen 2001). As a result, higher $\delta^{15}N$ values of organisms within a particular food web can indicate an upper trophic position such as a predator, while a low $\delta^{15}N$ value indicates a lower trophic position such as an algal feeder. Because the concentrations of contaminants such as Hg or organochlorines also increase with trophic position, leading to highest concentrations in top predators, there is a correlation with increasing $\delta^{15}N$ values in biota (Cabana and Rasmussen 1994). The slopes of regressions of log-transformed Hg concentration against $\delta^{15}N$ values indicate the rate of biomagnification within the food web (Atwell *et al.* 1998, Bowles *et al.* 2001, Kidd *et al.* 1995a). In addition, the intercepts of these regressions can provide a means of comparing contaminant levels entering the food (Kidd 1998).

Napoleon Gulf and Winam Gulf in northern Lake Victoria provide an opportunity to compare the food web structure and Hg bioaccumulation patterns between different environments with similar fish assemblages within the same lake. Napoleon Gulf, the source of the Nile River, and Winam Gulf, a large isolated bay, both face increasing environmental pressures including contaminant loading from urban, rural, and atmospheric sources and increasingly scarce fishery resources. In a linked paper in this issue (Campbell *et al.* 2003a), the food web structures of Napoleon and Winam gulfs have been characterized using stable nitrogen and carbon isotope ratios. For this paper, Hg distribution and bioaccumulation patterns were determined in each gulf and the distribution of Hg in water across northern Lake Victoria was used to assess spatial variation of Hg concentrations and background water THg and MeHg concentrations.

METHODS

The two sampling sites, Napoleon Gulf and Winam Gulf, are described in the previous paper (Campbell *et al.* 2003a). Napoleon Gulf is situated in southeastern Uganda. It is lightly industrialized with sugar processing, textiles, a brewery, and a major dam located on the outflowing Nile River. Napoleon Gulf is eutrophic, with convoluted bays and variable depths. Samples collected from the near shore Jinja Ferry Pier, the Buvuma Channel near the prison, and in Jinja Bay are included in the study (Fig. 1). Winam Gulf is in western Kenya (Fig. 1). It is shallow throughout its length and heavily industrialized (heavy industry, paint, solvent, and plastics manufacturing, as well as sugar, food, and fish processing). The gulf also receives a significant loading of municipal sewage (often untreated) from the city of Kisumu and nearby towns.

Biota sampling protocols followed trace-metal protocols, and are described in the previous paper (Campbell *et al.* 2003a). Sampling took place in Napoleon Gulf between October and November 1998 and in Winam Gulf in December 1998. It was not possible to maintain the same sampling protocol and effort for each site due to logistical constraints, but every attempt was made to collect a broad and diverse sample set and to collect a wide size range for Nile perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*). Fish were obtained by trawling the region and supplemented by overnight gill net sets and fish purchased directly from the local fishermen. All fish were dissected, and for the large fish, a 10-cm^3 muscle sample was collected from the lateral muscle. Smaller fish were filleted. Invertebrates were collected from the research vessels, canoes, or along the shoreline using collecting nets. Samples were wrapped in hydrochloric-acid cleaned aluminum foil, double-wrapped in Ziploc©, bags and frozen.

Water samples for Hg analyses were collected using ultra-clean techniques (Bloom 1994) with a peristaltic pump and platinum-treated silicone tubing. Approximately 60 mL of lake water were collected into Teflon© bottles at two depths at each site: 0.5 meters and at the thermocline, and are listed in Table 1. The thermocline in Lake Victoria is not as stable as for the Laurentian Great Lakes (Spigel and Coulter 1996), but exists when the lake is stratified from October to May (Hecky 1993, Hecky *et al.* 1994, Muggide 2001). Ten duplicate samples were taken within the same areas as the food web sampling sites (Fig. 1). In addition, six

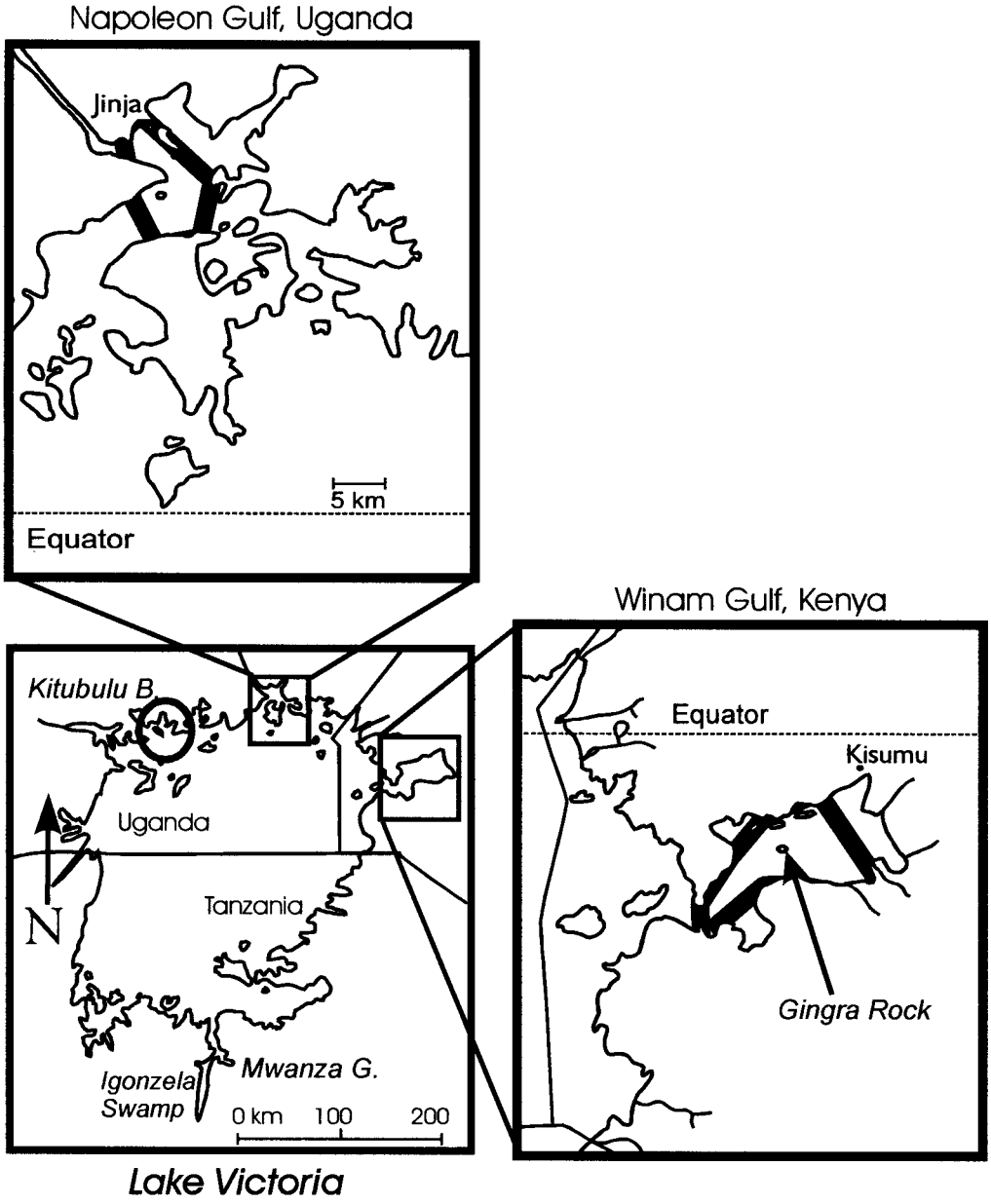

FIG. 1. Maps of Lake Victoria showing the location of sampling areas in Winam and Napoleon gulfs.

duplicate samples were collected at Itome Bay in Napoleon Gulf, offshore Bugaia Island, and two urban sites near Entebbe (Kitibulu Bay), and near Kisumu (Fig. 1). GIS co-ordinates were measured whenever possible. In Jinja Bay of Napoleon Gulf, four sites were selected to include possible anthropogenic and natural influences on Hg cycling (as a part of planned longer-term Hg cycling study). The "Prison" site is by the working prison located just outside of Jinja and is near a sewage-contaminated stream; "Jinja Bay" is an exposed site in the middle of the bay before it narrows into the Nile River; "Jinja Pier" is a site located between the tracks on a ferry loading pier which occasionally experiences petroleum fuel contamination; and the "Water Hyacinth" site is where massive build-up of the floating weed (*Eichhornia crassipes*) occurred near the pier (Table 1). Immediately after collecting, water samples were preserved with 1 mL of pure assayed HCl. Upon return to the laboratory, the water sam-

TABLE 1. THg and MeHg concentrations, temperature, dissolved oxygen (DO), pH, and conductivity for two different depths (0.5 and thermocline) at each site in northern Lake Victoria. The Napoleon Gulf sites (Prison, Jinja Bay, Water Hyacinth, and Jinja Pier) are located close to each other (see text). "n.a." indicate that logistics prevented measuring that aspect.

Site	GPS lat / long	Date d/m/y	Depth (m)	THg (ng/L)	MeHg (ng/L)	Temp (°C)	DO (mg/L)	pH	Cond. µmho/cm
Winam Gulf									
Kisumu	00°06′07″ S	12 Dec 98	0.5	4.5	n.a.	27.1	7.31	7.7	179
	34°44′35″ E		3	3.6	n.a.	26.8	7.31	7.7	179
Gingra Rock	00°20′43″ S	14 Dec 98	0.5	2.9	n.a.	27.7	8.18	8.1	177
	34°26′40″ E		6	3.3	n.a.	26.1	6.31	7.9	169
Napoleon Gulf									
Prison	00°24′24″ N	25 Oct 98	0.5	5.8	1	25.6	5.5	8.0	105
	32°03′97″ E		15	3.2	0.7	25.2	2.3	6.5	97
Jinja Bay	00°25.0′ N,	18 Nov 98	0.5	3.9	n.a.	26.2	7.1	8.8	98
	33°00′ E		8.5	1.7	n.a.	25.4	6.3	7.0	97
Water Hyacinth	00°25.0′ N,	18 Nov 98	0.5	2.3	0.2	27.4	7.8	9.0	99
	33°12.5′ E		2	2.3	0.2	27.1	6.7	8.6	99
Jinja Pier	00°25.0′ N,	29 Nov 98	0.5	2.8	n.a.	26.7	7.8	8.2	99
	33°12.5′ E		5	1.9	n.a.	25.9	6.2	7.9	97
Itome Bay	00°21′ 14″ N	27 Oct 98	0.5	3.4	n.a.	25.8	6.4	8.3	n.a.
	31°E		16	1.9	n.a.	24.7	3.1	6.5	n.a.
Bugaia Island									
Offshore site	00°04′ 11″ S	26 Oct 98	0.5	4	0.7	24.7	5.3	7.3	97
	33°16′ 08″ E		41	1.8	0.3	24.5	3.1	6.7	95
Kitubulu Bay									
near Entebbe	n.a.	03 Nov 98	0.5	3.2	n.a.	26.2	n.a.	n.a.	n.a.
	n.a.		5	3	n.a.	25.9	n.a.	n.a.	n.a.

ples were stored at –10°C until shipment to Canada in coolers. MeHg analyses were done for water samples from two sites in Napoleon Gulf ("Prison" and "Water Hyacinth"), and from Bugaia Island. Measuring probes were used to measure dissolved oxygen (YSI Incorporated, Model 57), pH (ORION model 250A), temperature and conductivity (ORION model 122).

Protocols for stable isotope analyses have been previously described and detailed (Campbell *et al.* 2003a). Briefly, small sub-samples of fish and invertebrate tissue were freeze-dried and ground into fine powder. Stable nitrogen and carbon isotope analyses were done concurrently using a Micromass VG-Isochrom Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS) at the Environmental Isotope Laboratory at University of Waterloo. The ratios of the stable nitrogen isotopes were measured against the reference standard, nitrogen gas in ambient air. The delta notation (δ) is used to indicate the parts per thousand (‰) difference in the isotopic ratio of the sample from the reference standard. Working standards included the International Atomic Energy Agency (IAEA) standards and in-house walleye and cellulose standards. Replicate Nile perch samples were included in every run to determine between-run variation.

THg analyses of biotic tissue were performed in the clean-room laboratory of Dorset Research Centre, Ontario Ministry of the Environment, Dorset, Ontario. Ultra-clean protocols were employed throughout the processing (Ontario Ministry of Environment 1999). Equipment and containers were cleaned with a strong oxidizing solution (20% nitric acid, 2% hydrochloric acid, and 0.05% potassium dichromate) and rinsed throughly. Clean-room suits and powder-free gloves were worn throughout cleaning and sample preparation. The samples were oven-dried, weighed, transferred to clean borosilicate test tubes, and digested in 2 mL of 1:4 nitric-sulfuric acid at 255%C for 6 hours. After cooling, 10 mL of Hg-grade distilled water was added to each sample and allowed to cool again. National Research Council (Canada) certified reference materials DORM-2 (4.64 ± 0.26 mg Hg /kg; Recovery = 110–125%) and DOLT-2 (2.14 ± 0.28 mg Hg /kg; Recovery = 97–120%) and blanks (less than 0.5 pg total) were also digested and processed in the same

manner as the samples to monitor the extraction efficiency of the digestions and any potential contamination. After processing, all test-tubes were vortexed throughly, and 0.5 mL of the digestate was transferred to a Teflon© tube containing 50 mL of a carrier solution (1.25% hydrochloric acid, sodium chloride and hydroxylamine hydrochloride in Hg-grade water). Each run included external standards (0 pg, 500 pg and 1,000 pg total Hg) made up from FisherScientific™ Hg reference standard (1,000 ppm ± 1%). Replicate samples were included in most runs to determine between-run variation (each replicated sample had a standard deviation of ±2.9 to ±10.5, with the highest standard deviation range belonging to larger Nile perch samples). Internal laboratory comparison of external standards were conducted regularly to ensure the accuracy of the standard solution.

The Hg concentration in each biotic sample was determined via atomic fluorescence spectroscopy (AFS) using the purge-and-trap procedure (Ontario Ministry of Environment 1999). The detection limit was 10 pg total Hg per sample. A Gilson model 200 automatic sampler delivered the entire solution from each Teflon© tube to a purge vessel, where 15 mL of 0.1 N sodium borohydride (to reduce free Hg^{2+} to Hg^0) was added. The sample was then purged with Hg-free argon gas and flushed into a trap containing gold mesh. After pre-concentration, the Hg was thermally desorbed and flushed into the detector. After every five samples, a 0.1 N solution of sodium chloride was processed through the set-up to rinse out any sorbed Hg. Sensitivity drift occurred during the run and was corrected by adjusting for the correct values of the external standards. Replicate samples were included in every run to determine between-run variation which was 2 to 7%.

The 1998 to 1999 Hg water samples were preserved with assayed ultra-pure HCl, stored at –10°C, sent to an ultra-clean laboratory (Flett Research Ltd., 440 Desalaberry Ave., Winnipeg, Manitoba, R2L –0Y7, Canada) and, immediately upon arrival, analyzed for Hg and MeHg. The total Hg was measured following the EPA Method 1631 which uses $SnCl_2$ to reduce THg in water samples, followed by gold amalgam trapping and fluorescence detection (U.S. E.P.A. 1999). The MeHg measurements employed an ethylation step followed by purge and trap/gas chromatography separation and fluorescence detection. Recovery of spiked samples averaged 86% (83 to 90%) with obvious but gradual decay in THg over time.

Statistical analyses were done in SYSTAT version 9.0 for Windows (SPSS Inc.), with significance at ≥ 0.5. Because international standards use weight-wet concentrations, the dry-weight THg concentrations were converted to wet weight using a factor of 0.31 for fish (Ramlal *et al.* 2003) and 0.25 for invertebrates (obtained by comparing wet-weight and dry-weight of whole invertebrates). Nile perch and Nile tilapia were grouped in size classes (see Table 1) based on previous work with dietary patterns in these fish species (Ogutu-Ohwayo 1994, Hughes 1986). Grouped t-tests were used to compare total length-normalized THg concentrations in Nile tilapia and Nile perch between the two gulfs. The bioaccumulation of Hg within the food web was determined by regressing log-transformed wet weight Hg concentrations against stable nitrogen isotope ratios. The slopes and intercepts were compared using ANCOVA in the General Linear Model function in SYSTAT.

Winam Gulf biota had more enriched $\delta^{15}N$ and more depleted $\delta^{13}C$ values than the same taxa in Napoleon Gulf and the differences were consistent between the same taxa in each gulf due to the different basal $\delta^{15}N$ and $\delta^{13}C$ values at the base of the food web (Campbell *et al.* 2003a). In the previous paper, the Napoleon Gulf stable isotope database was "adjusted" to the Winam Gulf stable isotope values to remove the consistent differences between $\delta^{13}C$ and $\delta^{15}N$ of biota. This was done by assuming that differences in intercepts ($\delta^{13}C$ = 4.02‰; $\delta^{15}N$ = 3.14‰) between regressions of selected Napoleon and Winam gulf biota represented the differences in basal isotopic signatures. The differences were used to adjust the $\delta^{13}C$ and $\delta^{15}N$ values of Napoleon Gulf biota to Winam Gulf basal values, and it was found that the food web structure in both gulfs were similar (Campbell *et al.* 2003a). To remove some of the variation incurred by significantly different basal stable isotope values, the adjusted $\delta^{15}N$ values from Napoleon Gulf were also regressed against log-transformed Hg concentrations. The log-THg:$_{adjusted}$ $\delta^{15}N$ regression was then compared to the Winam Gulf regression using ANCOVA.

During the sampling cruise in Winam Gulf, *Caridina nilotica* and *Rastrineobola argentea* (a small pelagic cyprind) were unknowingly contaminated by mercuric chloride used by other researchers for preserving water samples; these samples were excluded from statistical analyses. The Napoleon Gulf *R. argentea* values were also deleted from the statistical analyses to enable uni-

formity of the sample composition between the gulfs. Two fish species, *Schilbe intermedius* and *Synodontis afrofisheri*, were precluded from being important dietary items for Nile perch due to their highly depleted $\delta^{13}C$ values (Campbell *et al.* 2003a). These fish species were excluded from the Winam Gulf Hg analyses because there were no analogous samples from Napoleon Gulf to enable valid statistical comparisons. However, the Napoleon Gulf *R. argentea* and Winam Gulf *S. intermedius* and *S. afrofisheri* THg values are provided in Table 2 to allow informal comparison with other species and studies, especially as detailed Hg information are lacking for the Lake Victoria ecosystem.

TABLE 2. Mean (± s.d. with range and n) of THg and $\delta^{15}N$ values for fish and invertebrates from Napoleon (N) and Winam (W) gulfs. Asterisks indicate fish species that were not included in statistical analyses (see text). For detailed feeding patterns of each species, see Campbell* et al. *(2003a) in this issue. Mean ± standard deviations are calculated for biota which have three or more samples. Only the ranges are shown for biota which have only one or two samples.

		THg (ng/g ww)			$\delta^{15}N$ (‰)	
Species		n	mean ± s.d	range	mean ± s.d.	range
Invertebrates						
Caridina nilotica	N	5	21.1 ± 3.7	17.5–26.6	3.8 ± 1.0	2.1–4.7
Empheroptera	W	4	19.1 ± 0.4	18.6–19.4	7.12± 0.3	6.7–7.3
Mussels	W	2	~	19.6–25.0	~	7.1–7.8
Odonata	W	2	~	1.6–2.3	~	5.6–6.7
Planktivores						
Rastrineobola argentea *	N	3	16.3 ± 3.7	13.6–21.5	8.6 ± 0.6	8.5–9.4
Haplochromines	N	7	65.8 ± 13.9	52.0–84.8	8.3 ± 0.7	7.7–9.3
	W	3	14.4 ± 1.8	12.3–15.6	8.9 ± 0.6	8.6–9.6
Tilapia zilli	N	1	~	18.9	~	8.0
Quantitative planktivores						
Nile tilapia (Æ 5 cm)	W	3	13.4 ± 2.5	10.4–16.5	9.2 ± 0.6	9.0–10.4
Nile tilapia (5.1-20 cm)	N	7	18.6 ± 5.7	11.1–26.4	5.5 ± 0.6	4.6–6.3
Nile tilapia (20.1–40 cm)	N	3	32.5 ± 5.3	25.2–37.7	6.5 ± 0.4	6.0–6.9
	W	4	10.7 ± 2.4	7.8–13.1	8.6 ± 0.8	7.4–9.4
Nile tilapia (> 40.1 cm)	N	1	~	59.7	~	7.0
	W	8	28.3 ± 9.5	15.1–43.1	10.1 ± 0.6	9.4–10.7
Omnivores (invertebrates)						
Synodontis afrofischeri *	W	3	60.9 ± 8.1	53.6–72.2	9.9 ± 1.1	8.4–11.1
Omnivores (invertebrates & fish)						
Bagrus docmac	W	1	~	76.9	~	12.7
Clarius gariepinus	W	1	~	22.1	~	8.8
Protopterus aethiopicus	N	2	~	24.2–35.4	~	7.3–7.7
	W	3	20.3 ± 2.2	18.0–22.4	10.6 ± 0.5	10.1–11.1
Schilbe intermedius *	W	9	45.8 ± 17.6	22.2–78.6	9.5 ± 0.7	8.4–10.5
Predators						
Nile perch (≤ 5 cm)	W	2	~	25.43–27.80	~	9.09–9.45
Nile perch (5.1–20 cm)	N	3	76.0 ± 2.4	73.3–77.8	6.6 ± 0.1	6.5–6.6
	W	2	~	30.6–30.7	~	9.7–10.0
Nile perch (20.1–60 cm)	N	8	82.9 ± 16.9	69.1–115.5	8.2 ± 0.6	7.5–9.3
	W	8	36.4 ± 13.7	25.0–62.7	11.6 ± 1.4	9.2–13.4
Nile perch (60.1 -100 cm)	N	1	~	221.2	~	10.5
	W	4	89.1 ± 18.9	67.1–111.0	12.9 ± 0.3	12.6–13.3
Nile perch (> 100.1 cm)	W	1	~	323.1	~	11.8

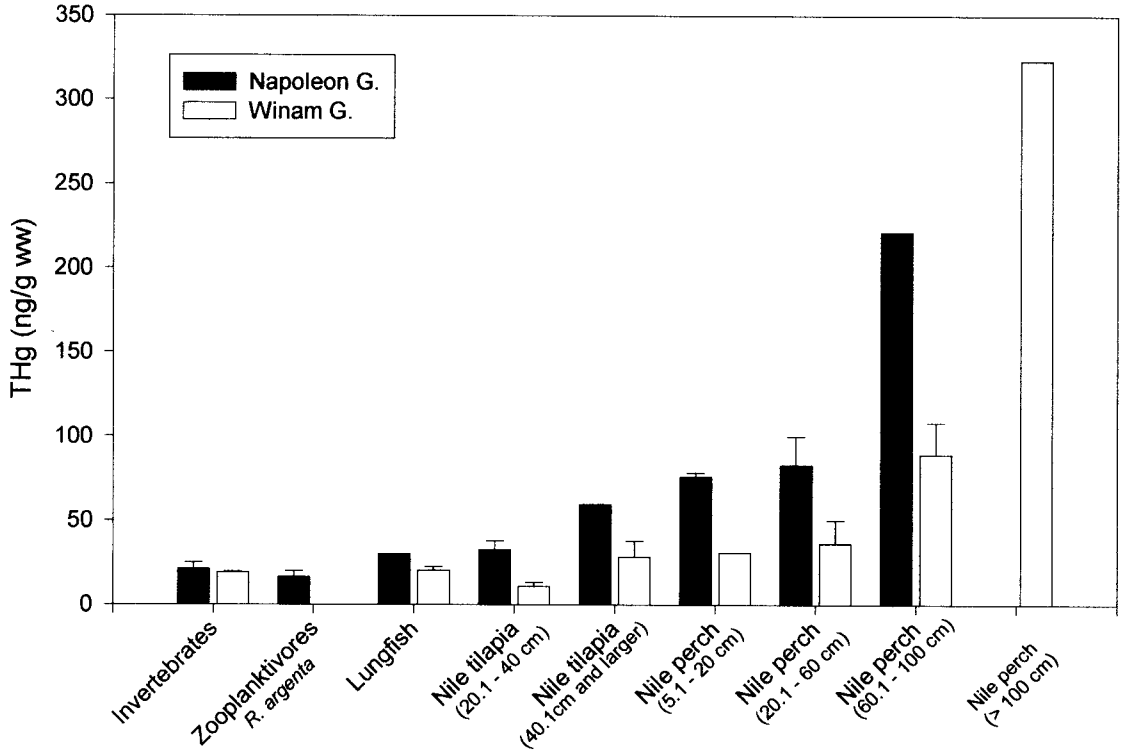

FIG. 2. Mean (± standard deviation) THg concentrations in selected biota from Winam (white) and Napoleon (black) gulfs.

RESULTS

Total Hg concentrations in water were variable across the region (Table 1), but higher concentrations tended to be near municipal sewage discharge sites (near Prison, Kisumu, and Kitibulu) and surface waters around Napoleon Gulf (Bugaia Island, Jinja Bay, and Itome Bay). The lower concentrations were found in the middle of Winam Gulf (Gingra Rock) and near-shore Napoleon Gulf (Jinja Pier, Water Hyacinth site) away from the municipal sewage discharge. Surface water samples consistently showed higher Hg concentrations than water samples taken at the thermocline in stratified waters. In well-mixed shallow sites, including Gingra Rock, Water Hyacinth site, and Kitubulu Bay, THg concentrations remained similar throughout the water column. MeHg concentrations were higher at the Prison and offshore Bugaia Island sites (0.3 to 1 ng/L), but were lower at the Water Hyacinth site (0.2 ng/L). The proportion of total Hg that was MeHg was fairly high at the Prison and Bugaia Island sites (16 to 23%) while it was low at the Water Hyacinth site (7 to 8%), indicating that net methylating activity can vary across Napoleon Gulf.

The invertebrates and most fish species in Napoleon Gulf have higher average THg concentrations than in Winam Gulf (Fig. 2, Table 2). THg concentrations normalized to total length (TL) in Nile perch (t, 2.73; df, 19; p, 0.027) were still significantly higher in Napoleon Gulf (3.4 ± 2.5 ng/g/cm) than in Winam Gulf (1.4 ± 0.6 ng/g/cm). The same is true for Nile tilapia (t, 5.42; df, 15.1, p, 0.000) which has higher THg concentrations in Napoleon (1.2 ± 0.4 ng/g/cm) than in Winam (0.5 ± 0.2 ng/g/cm). Larger fish in both gulfs tend to have higher THg concentrations than smaller fish of the same species (Table 2, Fig. 2). This is reflected in the significant regressions of log THg versus total length (TL) in both Nile tilapia and Nile perch from each gulf (Table 3). ANCOVA analyses indicate that the slopes of regressions are not significantly different between gulfs for each fish species, but the intercept for Napoleon Gulf fish are significantly higher than in Winam Gulf (Table 3).

Regressions of log THg against $\delta^{15}N$ values allow a statistical comparison of THg bioaccumulation in different food webs and can be used to discern whether Hg is being bioaccumulated through

TABLE 3. Regression of log THg concentrations in Nile perch and Nile tilapia from Winam and Napoleon gulfs versus total length (TL). The mean TL ± s.d. (and range) are given. Regression values (intercept, slope and adjusted r^2), and p-values are listed for ANCOVA results comparing the log THg:TL regressions. The alpha value for correlations is 0.027 and significance is determined at p-value ≤ 0.05. An extremely large Nile perch from Winam Gulf (TL = 158 cm) was excluded as an outlier.

ANCOVA Site	ANCOVA Object	TL (cm)	Intercept	Slope	r^2_{adj}	*p*- value	intercept	slope
Napoleon	Nile perch	41.3 ± 12.8 (15.0–62.0)	1.62	0.008	0.94	0.00	0.075	0.943
Winam		45.2 ± 24.9 (10.4–87.8)	1.33	0.008	0.86	0.00	″	″
Napoleon	Nile tilapia	22.10 ± 7.88 (15.5–41.8)	0.92	0.020	0.94	0.00	0.058	0.908
Winam		42.4 ± 8.26 (25.5–48.8)	0.393	0.020	0.99	0.00	″	″

the food webs at a similar rate. The regressions of log-transformed THg and $\delta^{15}N$ are significant (p, < 0.001) for Napoleon Gulf (Eq 1) and Winam Gulf (Eq 2: Fig. 3). ANCOVA regression comparisons indicate that while the intercepts for Napoleon Gulf is significantly higher (p, 0.011) than for Winam Gulf, the slopes are not different (p, 0.954).

$$\text{Log}_{10}\ \text{THg (Napoleon Gulf)} = 0.479 + 0.163\ (\delta^{15}N) \quad (n = 33,\ r^2 = 0.510) \qquad (1)$$

$$\text{Log}_{10}\ \text{THg (Winam Gulf)} = -0.276 + 0.165\ (\delta^{15}N) \quad (n = 37,\ r^2 = 0.683) \qquad (2)$$

Regressing the adjusted Napoleon Gulf data, which were "adjusted"to Winam Gulf values as described in Campbell *et al.* (2003a), the intercept has become lower than in the original data regression (Eq 3, Fig. 3B). ANCOVA analyses comparing the adjusted data with the original Winam Gulf database indicate that the intercepts are (barely) not significantly different (p, 0.481), although the Napoleon Gulf intercept is still higher than for Winam Gulf.

$$\text{Log}_{10}\ \text{THg (Adjusted Napoleon Gulf)} = -0.033 + 0.163\ (\delta^{15}N_{adj}) \qquad (3)$$

DISCUSSION

THg and MeHg concentrations in Lake Victoria are below Canadian drinking water guidelines of 100 ng/L (Health Canada 1996). To place the water Hg concentrations in Lake Victoria into an international perspective, a review of unfiltered water Hg concentrations in large lakes and tropical lakes around the world and other studies examining water Hg in L. Victoria is shown in Table 4. The exceptionally polluted temperate Onondaga Lake (chlor-alkali plant site) provides an extreme end-point, and as expected, this lake had the highest THg and MeHg concentrations in this short list. Compared to the temperate Great Lakes (Baikal, Ontario, Michigan, Erie), 1998 Lake Victoria water samples had THg concentrations that were an order of magnitude higher, and MeHg concentrations were even higher (by 2 to 3 orders of magnitude). In the tropics, Lake Maryout in Egypt had comparatively similar THg concentrations to those for the temperate Great Lakes, while Lake Murrary in Papua New Guinea had intermediate THg and MeHg concentrations (Table 4). Lake Naivasha in Kenya also had comparatively low THg concentrations (1.6 ng/L; Table 4), but its feeder streams had higher THg concentrations (1.8 to 12.1 ng/L; Table 4) which was associated with suspended particles (Bonzongo *et al.* 1996). The conditions leading to elevated water THg concentrations may be specific to Lake Victoria, and perhaps other East African lakes and are not related to latitude.

THg and MeHg concentrations in northern Lake Victoria show approximately two-fold variation across the sampling region. Water THg concentrations at 0.5 m ranged from 2.3 to 5.8 ng/L, while deep samples in stratified waters ranged between

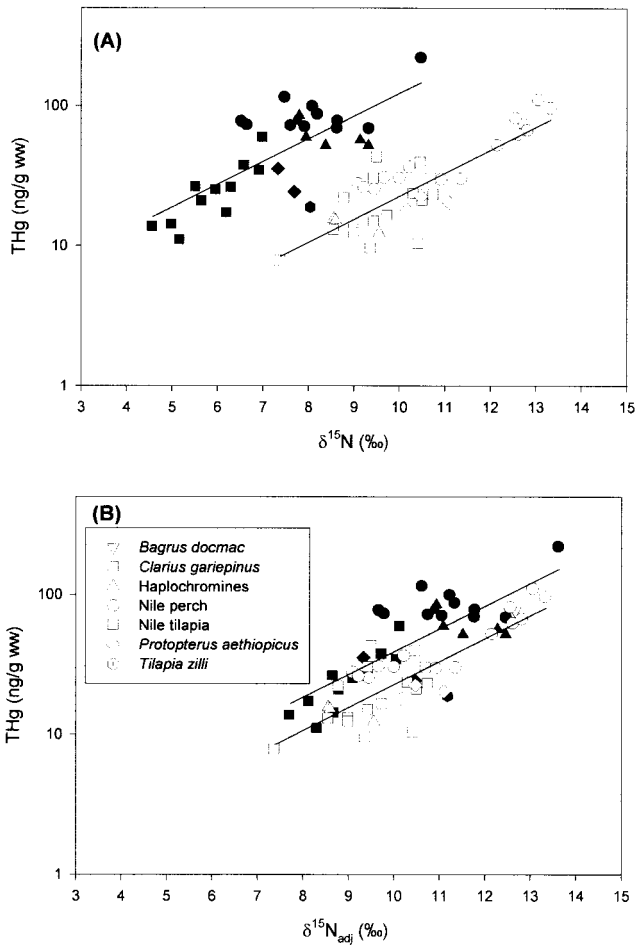

FIG. 3. Log-THg vs. $\delta^{15}N_{orginal}$ (A) and $\delta^{15}N_{adjusted}$ (B) values of individual biota from Napoleon (black) and Winam (white) gulfs. The regression lines are indicated, and the regression equations are in the text (Eqs. (1) and (2)). The $\delta^{15}N_{adjusted}$ values were obtained by "adjusting" Napoleon Gulf $\delta^{15}N$ basal values to those of Winam Gulf (see text).

1.7 and 3.2 ng/L. Water samples taken near municipal sewage discharge sites usually showed elevated THg and MeHg concentrations, an observation most likely explained by the increased loading of untreated sewage and increased bacterial methylation activity in these regions (Bodaly *et al.* 1998). The latter is borne out by the higher proportion of MeHg (16 to 23%) measured near the prison in Napoleon Gulf. Samples collected near the thermocline where the dissolved oxygen is lower than at the surface (3.1 mg/L vs. 5 to 6 mg/L), consistently show higher ratios of MeHg to THg than at the surface. This suggests that increased activity of methylating bacteria or the availability of the Hg^{2+} ion in THg fraction related to decreased oxygen levels, may be an important aspect of the Hg cycle in Lake Victoria. The proportion of 1998 MeHg in Lake Victoria is higher than for most lakes listed in Table 4 except for thermocline values from Onondaga Lake. The 1995 Napoleon Gulf study has demonstrated THg values similar to the 1998 values, but reported lower MeHg concentrations (Table 4). The 1995 Napoleon Gulf MeHg concentrations were still higher than for the temperate great lakes by 1 to 2 orders of magnitude (Ramlal *et al.* 2003). The variable MeHg concentrations in 1995 and 1998 (collected in October and November of both years) indicate that rates of methylation may vary temporally in Lake Victoria. The combination of the relatively shallow stratified region near the prison, tropical warmth, and putative sources of sewage, both from the municipality and the prison, may be leading to increased but variable methylation activity at this site.

It is interesting that Itome Bay and Bugaia Island water samples show THg concentrations similar to those seen at the more contaminated sites in Lake Victoria, despite their locations away from industrial or heavily populated sites. Both sites, however, are situated near islands that are subject to frequent biomass burnings for agricultural land renewal. The sites with lowest Hg concentrations, Gingra Rock in Winam Gulf, Jinja Pier, and Water Hyacinth, are all near land; all those sites have well-mixed shallow depths that may be constantly moving Hg compounds through the water column. Shallow depths in Lake Victoria favor high rates of light-dependent processes (Muggide 2001), so sunlight could be an important factor in the Hg cycling in this lake. The intense tropical solar radiation in addition to the constant cycling of Hg to the water surface at these sites may lead to increased volatilization and evasion of Hg^0 to the atmosphere due the photochemical reduction of dissolved Hg to Hg^0 (Amyot *et al.* 1997a).

Lake Victoria is stratified much of the year and a well defined thermocline is in place in the wet season from October through May (Hecky 1993, Hecky *et al.* 1994, Muggide 2001). Stratification and the subsequent thermocline formation in the lake influences nutrient and iron cycling (Hecky *et al.* 1996, Muggide 2001). Suspended particulates also tend to be higher at the surface than at depth and are higher near-shore than offshore. For example, measured suspended N, P, and C for Bugaia Is-

TABLE 4. Published values for THg and MeHg concentrations in water from various lakes, including studies in Ugandan (Ug) and Tanzanian (Tz) areas of Lake Victoria. All lakes were sampled between 1990 and 2000 except for Onondaga Lake (1989). Note that many studies that employed filtration methods often listed total unfiltered values for THg and MeHg. A cross indicates that the water samples were filtered. (n.d. = not detected; n.a. = not analyzed).

Lake	Year	Depth	THg (ng/L)	MeHg (ng/L)	References
L. Ontario, Canada	1998	Surface	0.31–0.99	n.a.	Amyot *et al.* 2000
L. Michigan, USA	1994–95	various	0.29–0.38	0.013	Mason and Sullivan 1997
L. Erie, Canada	1994	Surface	0.3	n.a.	Amyot *et al.* 1997b
L. Baikal, Russia	1992–93	various	0.14–0.77	0.002–0.038	Meuleman *et al.* 1995
L. Maryout, Egypt	1996–97	unknown	0.25 ± 0.004	n.a.	El-Demerdash and Elagamy 1999
L. Murray, Papua New Guinea	1995–96	unknown	1.4 ± 1.3	0.07–0.12	Bowes *et al.* 2001
L. Naivasha, Kenya	<1996	surface	1.6 ± 0.2	n.a.	Bonzongo *et al.* 1996
L. Naivasha rivers	<1996	surface	1.8 ± 0.2	12.1 ± 0.1	
Onondaga L., USA	1989	0 m	7.1–18.8	0.4–2.0	Bloom and Effler 1990
	1989	18 m	10.1–25.7	1.6–6.7	
L. Victoria Upstream of Igonzela Swamp (Tz)	1997	Surface	n.d.–400†	n.a.	van Straaten 2000
Downstream of Igonzela Swamp	1997	Surface	n.d.–100†	n.a.	
Bugaia Island (Ug)	1995	10 m	3.6	n.a.	Ramlal *et al.* 2003
	1995	40 m	15.5	n.a.	
	1998	0.5 m	4.0	0.7	This study
	1998	40 m	1.8	0.3	This study
Prison Stream					
Napoleon Gulf (Ug)	1995	Surface	n.a.	0.14	Ramlal *et al.* 2003
	1998	0.5 m	5.8	1.0	This study
Water Hyacinth, Napoleon Gulf (Ug)	1995	Surface	n.a.	0.06–0.13	Ramlal *et al.* 2003
	1998	0.5 m	2.3	0.2	This study

land in November 1998 were 138, 14, and 700 μg/L at 0.5 m and 40, 4, and 280 μg/L at 40 m, respectively (Muggide 2001). For Napoleon Gulf near the prison, surface SN, SP, and SC were 819, 80, and 4,060 μg/L while at 15 m, SN, SP, and SC were measured as 162, 22, and 760 μg/L respectively (Muggide 2001). The presence of higher THg and MeHg concentrations at the surface of temporarily stratified waters, along with higher concentrations of C, N, and P particulates, point to the possible importance of atmospheric sources of Hg to the lake, resulting in a rapid accumulation of Hg at the water surface in the wet season. It is still unknown how THg is distributed during the dry season when the lake mixes throughout its depth.

Erosion and runoff is a potential (but likely minor) source of THg runoff from regional rivers (20 km^3/yr inflow; Bootsma and Hecky 1993) are relatively low for a large lake, but can carry significant amount of soil into the lake (Lindenschmidt *et al.* 1998). Local soils in the Jinja area have low THg concentrations (34 ±11 ng/g dw THg; Campbell 2001), and lake sediments more than 100 ng/g THg indicating the tendency of lake sediments to receive and concentrate Hg per unit dry weight. The streams flowing into Lake Naivasha have been demonstrated to have elevated THg concentrations that are associated with suspended particulates and iron (Bonzongo *et al.* 1996). This may also apply to Lake Victoria, where soil is high in Fe-oxyhydroxides and may be an important terrestrial source of THg to the lake (Campbell *et al.* 2001b). Biomass burnings probably contribute a significant amount of THg to the atmosphere around Lake Victoria. A

significant proportion (≥ 50%) of global biomass fires seen in satellite observations are located in sub-Saharan Africa (Dwyer *et al.* 2000), and biomass burnings can emit large amounts of THg (Freidli *et al.* 2001). Published estimates have suggested that 300 metric tons of THg are released to the atmosphere by biomass burnings, including forests, savannas, and farmland, across Africa every year (Nriagu 1992). Concentrations of polycyclic aromatic hydrocarbons, byproducts of the combustion of wood and fossil fuel, are increasing in lake sediments (Lipiatou *et al.* 1996), providing further evidence of increased biomass burning and vehicular use in the watershed of Lake Victoria.

The role of sub-tropical wetlands in accumulating and methylating mercury is still under extensive research (the Florida Everglades), and even less is known about tropical lacustrine wetlands bordering large lakes, particularly in Africa. The Igonzela Swamp, one of the important wetlands feeding Smith Arm of Mwanza Gulf, is near gold processing sites where liquid Hg is used in gold extraction (van Straaten 2000). Prior to the Igonzela Swamp, stream water has elevated Hg concentrations reaching 400 ng Hg /L (when measured above unindicated detection limits) while while concentrations in the swamp water entering the lake are ≤ 100 ng Hg /L (Table 4). The lower THg concentrations in lake water indicates the importance of wetlands in contaminant removal. However, this is a two-edged sword: 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 reaching above storage capacity in polluted wetlands near urban areas have been flushed into Lake Victoria in all three countries (Kiremire 1998, Makundi 2001, Onyari and Wandiga 1989), and there is no reason to consider that THg or MeHg will behave differently in the tropical wetlands. The differences may lie in temperature-influenced methylation rates, higher UV radiation, and the high organic matter and oxyhydroxides in Lake Victoria wetlands. It is still unknown how these factors influence the Hg cycle in African lacustrine wetlands, and will be included in future research.

In several studies, the slope of the regression of log-transformed Hg concentrations and $\delta^{15}N$ values have been used as a quantitative measure of bioaccumulation rates within the food web. Published log Hg:$\delta^{15}N$ slopes from other studies ranged between 0.17 to 0.48 for temperate freshwater ecosystems (Kidd 1998). In this study, the log-transformed THg - $\delta^{15}N$ slopes were 0.163 for Napoleon Gulf and 0.165 for Winam Gulf. The slopes were not significantly different, indicating that the THg bioaccumulation rates are similar in each gulf. The regression slopes for log-THg:$\delta^{15}N$ for oligotrophic L. Malaŵi in southern Africa are 0.23 to 0.25 (Kidd *et al.* 2003). The highest THg concentrations in a piscivorous cichlid (*Ramphochromis cf. ferox*) in Lake Malawi is 200 ng/g, similar to larger Nile perch in Lake Victoria. The log-MeHg:$\delta^{15}N$ slope for tropical Lake Murray in Papua New Guinea is 0.28, with highest mean THg concentrations of about 500 ng/g in piscivore *Lates calcarifer* (Bowles *et al.* 2001). Precise comparisons of log Hg:$\delta^{15}N$ slopes for diverse food webs are difficult due to the variability in data and species composition, but does give an indication of biomagnification power for different ecosystems. The similar ranges of slope values in these tropical and temperate lakes indicate that THg in the freshwater ecosystem (that is not lost due to volatilization or sedimentation) are bioaccumulated in fish at relatively consistent rates.

Napoleon Gulf biota concentrations are consistently higher, but always by less than an order of magnitude, than the concentrations in Winam Gulf biota. Significantly different intercepts for the regressions of log-transformed Hg concentrations and original $\delta^{15}N$ values in each gulf indicate that the THg concentrations at the base of the food web are significantly different in each gulf. Even after removing the possible bias due to different basal stable isotope values, the log THg: $\delta^{15}N_{adj}$ regression resulted in a slightly higher intercept for Napoleon Gulf biota. In a previous paper in this issue, the food web structure for Winam and Napoleon gulfs were compared using $\delta^{15}N$ and $\delta^{13}C$ analyses, and there were no significant differences found in the length of the food web (as indicated by $\delta^{15}N$) between the two gulfs, nor in the food web structure (as indicated by $\delta^{13}C$) leading to Nile perch (Campbell *et al.* 2003a). Therefore, higher THg concentrations in Nile perch and other biota can be explained by the initial bio-available Hg concentrations in invertebrates and plankton at the base of the food web, not by any fundamental differences in the food web structure in each gulf nor the rate of bioaccumulation (as indicated by log THg:$\delta^{15}N$ slopes). This is confirmed by the similar slopes of the log THg vs. TL relationships for both Nile tilapia and Nile perch from each gulf, indicating that MeHg is

being bioaccumulated in growing fish at similar rates in both gulfs. The higher THg concentrations in Napoleon Gulf biota are not at levels considered to be a health risk nor an ecosystem issue, but it does suggest different factors may be influencing the methylation of Hg in each gulf. The factors accounting for the possible increase in bio-available Hg in Napoleon Gulf need to be identified in order to guard against increases in bio-available Hg in other parts of Lake Victoria.

The elevated concentrations of THg in Lake Victoria water would logically lead to an expectation of elevated concentrations in Nile perch, the top predator. Nile perch, however, have lower Hg concentrations than those in top piscivores in many other lakes. For example, cold-water pisicivorous fish such as walleye (*Stizostedion virteum*) and northern pike (*Esox lucius*) in Canadian lakes can have THg concentrations from 90 and 3,240 ng/g (Wren *et al*. 1991). In contrast, the largest Nile perch in this study, a 65 kilogram specimen (TL,158 cm) captured in Winam Gulf, "only" had about 323 ng/g THg. Four possibilities might explain why THg concentrations in Lake Victoria fish are so low despite high THg concentrations in water.

First, the food web length in Lake Victoria is short. There is no more than 8‰ difference in $\delta^{15}N$ values of the highest Nile perch and the lowest *C. nilotica*, and assuming a mean enrichment of 3 to 4‰ per transfer, this represents only one or two trophic transfers between the invertebrates at the base of the food web and the top predator (Campbell *et al.* 2003a). In addition, the same stable isotope analyses has led to the hypothesis that Nile perch populations in Lake Victoria may be self-limited by cannibalism, which can shorten the food web length (Campbell *et al.* 2003a). Short food web length means that THg has fewer biomagnification "steps" between top predators and lower trophic biota, thereby reducing the final biomagnified concentrations in top predators (Cabana and Rasmussen 1994, Rasmussen *et al*. 1990). This has been demonstrated using $\delta^{15}N$ to demarcate food web length for organochlorines and THg in same fish species from different lakes with differing food web structure (Kidd *et al*. 1995a, Kidd *et al*. 1995b). The reduced trophic position of Nile perch in Lake Victoria after the haplochromine crash (Ogutu-Ohwayo 1999) may be protecting this fish species from further elevated THg concentrations.

Second, rapid and consistent fish growth in Lake Victoria may lead to lower THg concentrations in fish compared to slower-growing temperate fish which have to survive in cold waters and contend with variable seasonal growth. Tropical fish tend to have increased metabolic rates due to the warm water temperatures and grow more rapidly than temperate fish (Pauly 1998), which would lead to a higher tissue production and lower THg concentrations. The same is assumed to hold for tropical invertebrates, which may to lead lower THg concentrations throughout the entire food web. For example, modeling experiments have shown that MeHg is excreted more rapidly in coldwater fish at warmer temperatures (Trudel and Rasmussen 1997). Also, a study comparing THg bioaccumulation in dwarf and normal lake whitefish (*Coregonus clupeaformis*) in northern Québec demonstrated that the slow-growing dwarf whitefish bioaccumulate THg more rapidly than the normal whitefish despite similar THg content of their prey (Doyon *et al.* 1998).

Third, biomass dilution, the distribution of Hg in a larger volume of biota and organic matter (both dissolved and suspended), may be a factor in Lake Victoria. This hypothesis has been proposed to explain why the uptake of Hg in fish from different Swedish lakes with varying trophic and chemical parameters could not be correlated to the original Hg in sediment or water. Instead, the uptake of Hg was related to the amount of autochthonous organic matter within the lake and was inversely proportional to the biomass at the base of the food web, resulting in biodilution (Meili 1994). Lake Victoria is highly eutrophic and likely has a greater amount of biomass at all trophic levels compared to other lakes. Average chlorophyll-a concentrations, often used as an indicator of standing phytoplankton biomass, are 4.7 to 78.5 mg/L (mean 26.5 ± 15.9 mg/L; Guildford and Hecky 2000) in near-shore Napoleon Gulf and 8.8 to 71.5 mg/L (approximate mean ~20 mg/L; Lung'ayia *et al.* 2000) in Winam Gulf. In other great lakes in Africa (except the hyper-eutrophic Lake Albert) and North America, chlorophyll rarely exceeds 8 mg/L (Hecky 2000). Despite increased Hg concentrations in water, the bioaccumulation of Hg may be slowed by both the increased amount of plankton assimilation and the greater diversity of fish and invertebrates in the food web of Lake Victoria.

Fourth, the biogeochemistry of Hg in Lake Victoria may reduce the availability of Hg for biotic uptake. MeHg is rapidly and easily assimilated by biota, but other forms of Hg, including inorganic Hg, are not as easily assimilated (Morel *et al.*

1998). Methylation of Hg compounds occurs with microorganisms catalyzing the reaction forming the covalent bonds between Hg and CH_4. The presence of chloride, organic compounds, and sulfur influences the type of the microorganisms and their ability to take up and methylate Hg (Morel *et al.* 1998). A shift in the bacterial composition and activity or chemical equilibrium can lead to increased methylation of Hg compounds (Hecky *et al.* 1991, Lindqvist *et al.* 1991). Decreased sulfate fluxes can lead to decreased MeHg concentrations because methylation rates due to sulfate-reducing bacteria is repressed (Hudson *et al.* 1994). Sulfate concentrations (13 to 16 mM) and net sulfate reduction are low in Lake Victoria (Ramlal *et al.* 2003) which may be leading to the low MeHg concentrations in the water column despite high THg concentrations.

Biogeochemical influences on Hg cycling may also explain why Winam Gulf fish have lower THg than for Napoleon Gulf fish despite similar THg concentrations in water. Apparently, there is lower bioavailability of Hg to fish in Winam Gulf, which may be due to a reduced net rate of methylation in the gulf. Winam Gulf is nearly closed to the main lake and its waters have a higher conductivity (169 to 179 μmho/cm). Napoleon Gulf, open to the lake, is constantly flushed by the Nile River and has lower conductivity (95 to 105 μmho/cm; Table 1). The higher conductivity indicates increased ionic concentrations in Winam Gulf. For example, increased sulfate concentrations have been measured in Winam Gulf (0.316 μg/L) relative to the open lake (0.08 μg/L; Kilham 1971). While sulfate has been associated with stimulating sulfate-reducing bacteria to methlyate Hg in anoxic conditions, in well-mixed waters of Winam Gulf, increasing sulfate indicates more sulfide which can bind to Hg^{2+}, thereby removing it from methylation (Morel *et al.* 1998). DOC concentrations are higher in Winam Gulf (6.1 to 7.8 mg/L) than in Napoleon Gulf (2.7 to 3.0 mg/L; unpubl. data). Hg^{2+} can form strong chelation bonds to amino acids in DOC compounds (Nriagu 1994), which may result in less bio-available Hg in Winam Gulf. As previously mentioned, Winam Gulf is shallow, and often is highly mixed, which may lead to higher evasion of Hg^0 to the atmosphere due to the intense tropical solar radiation (Amyot *et al.* 1997a), likely resulting in higher net losses of THg compared to Napoleon Gulf.

Even though the human health risk from consuming fish in the Lake Victoria region is low (Campbell *et al.* 2003c, Harada *et al.* 1999, Ikingura and Akagi 1996), the fact that Hg concentrations in Lake Victoria water are higher than those in temperate great lakes by at least an order of magnitude (Table 4) points to the potential for an increased human health risk if the Hg methylation balance shifts in the future to favor increased production. For example, low ambient sulfate concentrations may not be enough to prevent the methylation of Hg compounds if the lake becomes increasingly eutrophic and anoxic and if the human populations around the lake increases. Increasing organic matter and sulfur loading can mediate Hg reactions and have been associated with increased MeHg (Sjöblom *et al.* 2000). Hg compounds bind strongly to oxyhydroxide particulates (Morel *et al.* 1998), particularly these which are common components of soil (as Fe-oxyhydroxides) around Lake Victoria (van Straaten 2000). When those Hg-bound oxyhydroxide particulates in the lake drop below the oxic-anoxic zone, Hg compounds are frequently released into the water column (Morel *et al.* 1998). Sulfur compounds are one by-product of petrol combustion and can be atmospherically deposited on the lake as "acid rain" which can decrease the pH and add sulfate to the water column, thereby increasing the methylation of Hg compounds (Gilmour and Henry 1991). All those are increasingly plausible in Lake Victoria in the near future, and with a large reservoir of THg in the water column, it is important to monitor any changes and potential impacts to avoid unsafe THg concentrations in the fish.

To summarize, water THg concentrations in Lake Victoria are similar across the northern region and are higher than these seen in temperate great lakes and most tropical lakes which is in agreement with a similar study in Napoleon Gulf (Ramlal *et al.* 2003). The THg concentrations in fish and invertebrates are relatively low in both Winam and Napoleon Gulfs compared to these from other large temperate lakes, In this study, the highest THg concentrations occurred in biota from Napoleon Gulf. THg concentrations increased with size in both Nile perch and Nile tilapia, with the largest piscivore Nile perch having the highest concentrations in both gulfs. The bioaccumulation of THg in the food webs of Napoleon and Winam gulfs is occurring at similar rates as indicated by similar slopes of log-THg - $\delta^{15}N$ regressions. The low THg concentrations in fish and invertebrates seem contrary to high THg concentrations in water and are attributed to four probable factors: short food web length, increased growth dilution and tissue turnover in tropical biota, biomass dilution, and the unique

biogeochemistry of Lake Victoria. However, it is important to point out that any shift in the methylation process, trophic status, or food web structure in Lake Victoria, especially if the lake becomes increasingly eutrophic and hypoxic (thereby simulating growth of methylating microrganisms), could lead to increased bioaccumulation of MeHg in the food chain.

ACKNOWLEDGMENTS

The staff and scientists at 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 various sampling trips and provided laboratory and storage space. Dr. Greg Mierle and Don Evans (Dorset Environmental Research Centre, Ontario Ministry of Environment and Energy) lent laboratory space and the use of Hg analysis equipment. William Mark assisted with stable isotope analyses at the Environmental Isotope Laboratory, University of Waterloo. Dr. Jeanette O'Hara-Hines (Department of Statistics and Actuarial Sciences, University of Waterloo) provided statistical consultation. Financial support was provided by a NSERC PS-B Graduate Scholarship and an International Development Research Council Doctorate Award to Linda M. Campbell and NSERC research grants to R. E. Hecky and D. G. Dixon.

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Submitted: 15 August 2001
Accepted: 2 January 2003
Editorial handling: Derek C.G. Muir

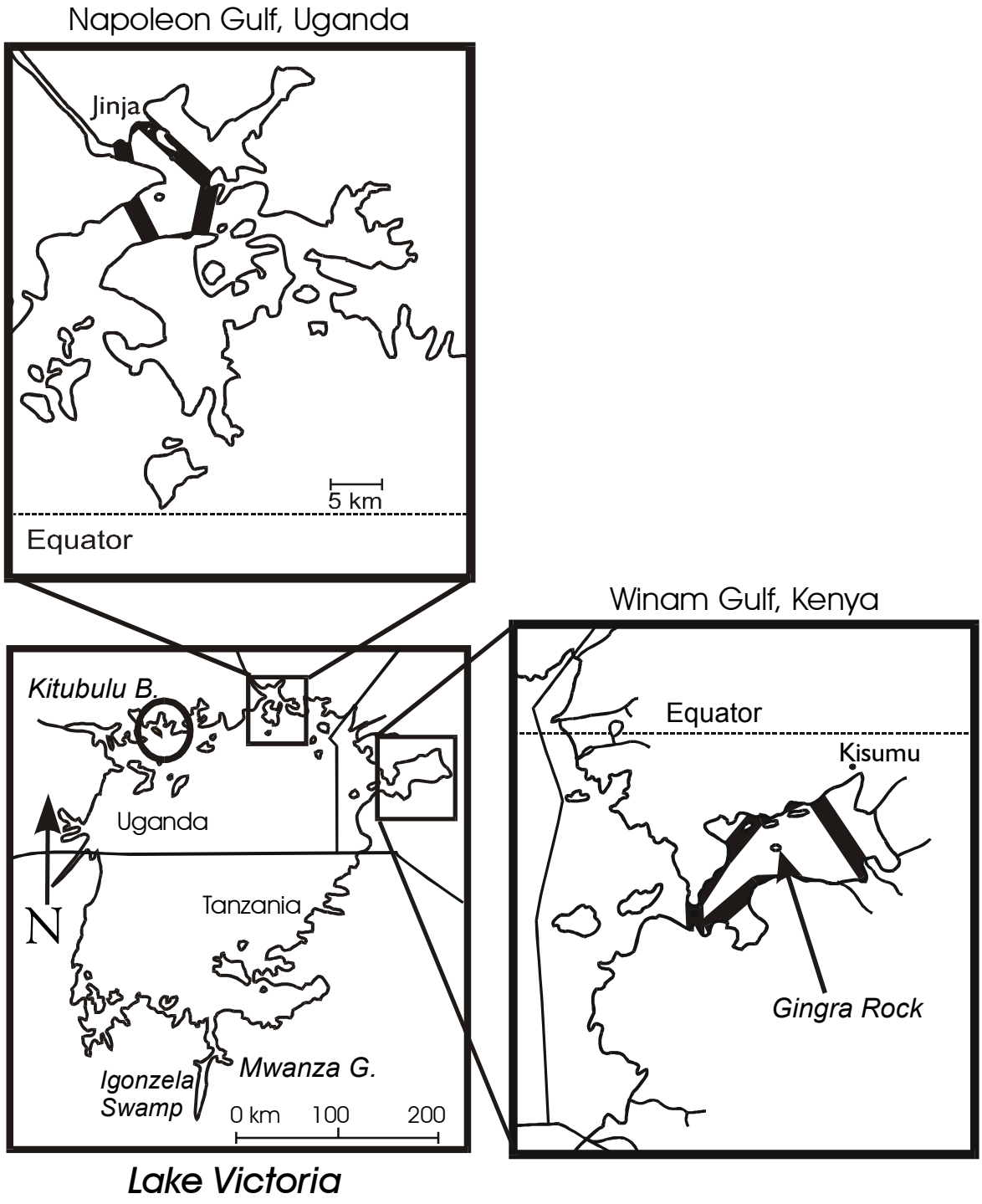
Napoleon Gulf, Uganda
Jinja
5 km
Equator
Winam Gulf, Kenya
Kitubulu B.
Uganda
Tanzania
N
Igonzela
Swamp
Mwanza G.
0 km 100 200
Lake Victoria
Equator
Kisumu
Gingra Rock

Figure 1.

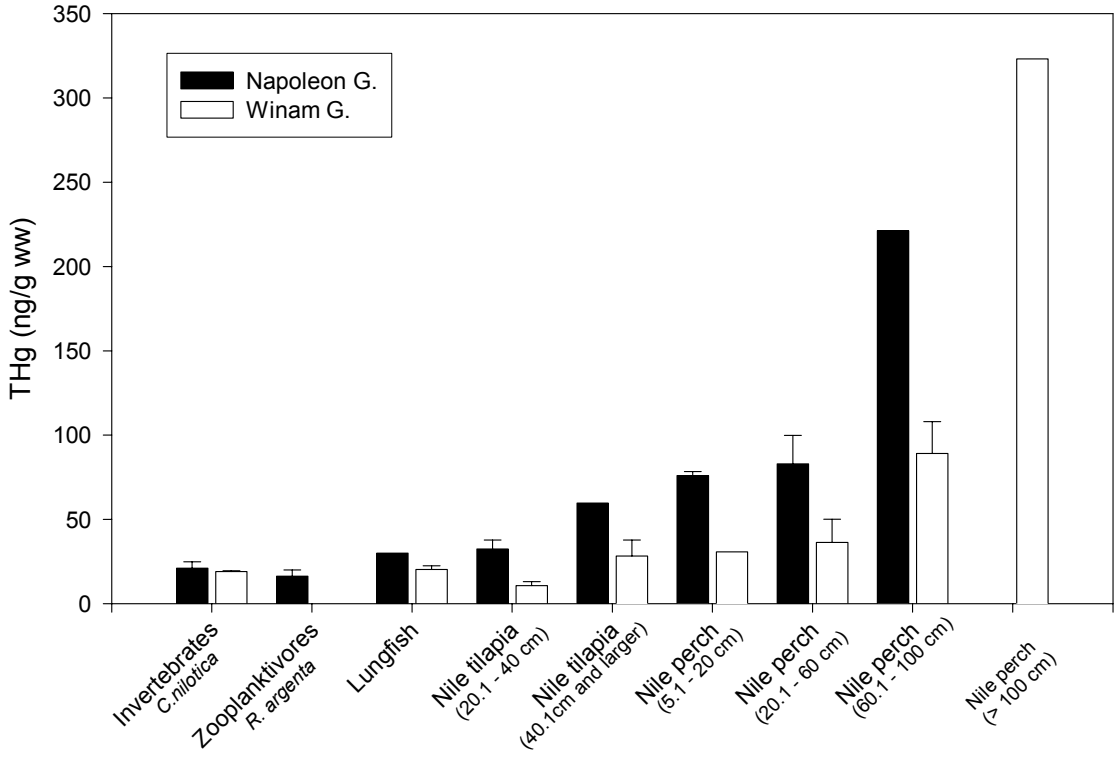
350
300
250
200
150
100
50
0
THg (ng/g ww)
Napoleon G.
Winam G.
Invertebrates
C.nilotica
Zooplanktivores
R. argenta
Lungfish
Nile tilapia
(20.1 - 40 cm)
Nile tilapia
(40.1cm and larger)
Nile perch
(5.1 - 20 cm)
Nile perch
(20.1 - 60 cm)
Nile perch
(60.1 - 100 cm)
Nile perch
(> 100 cm)

Figure 2.

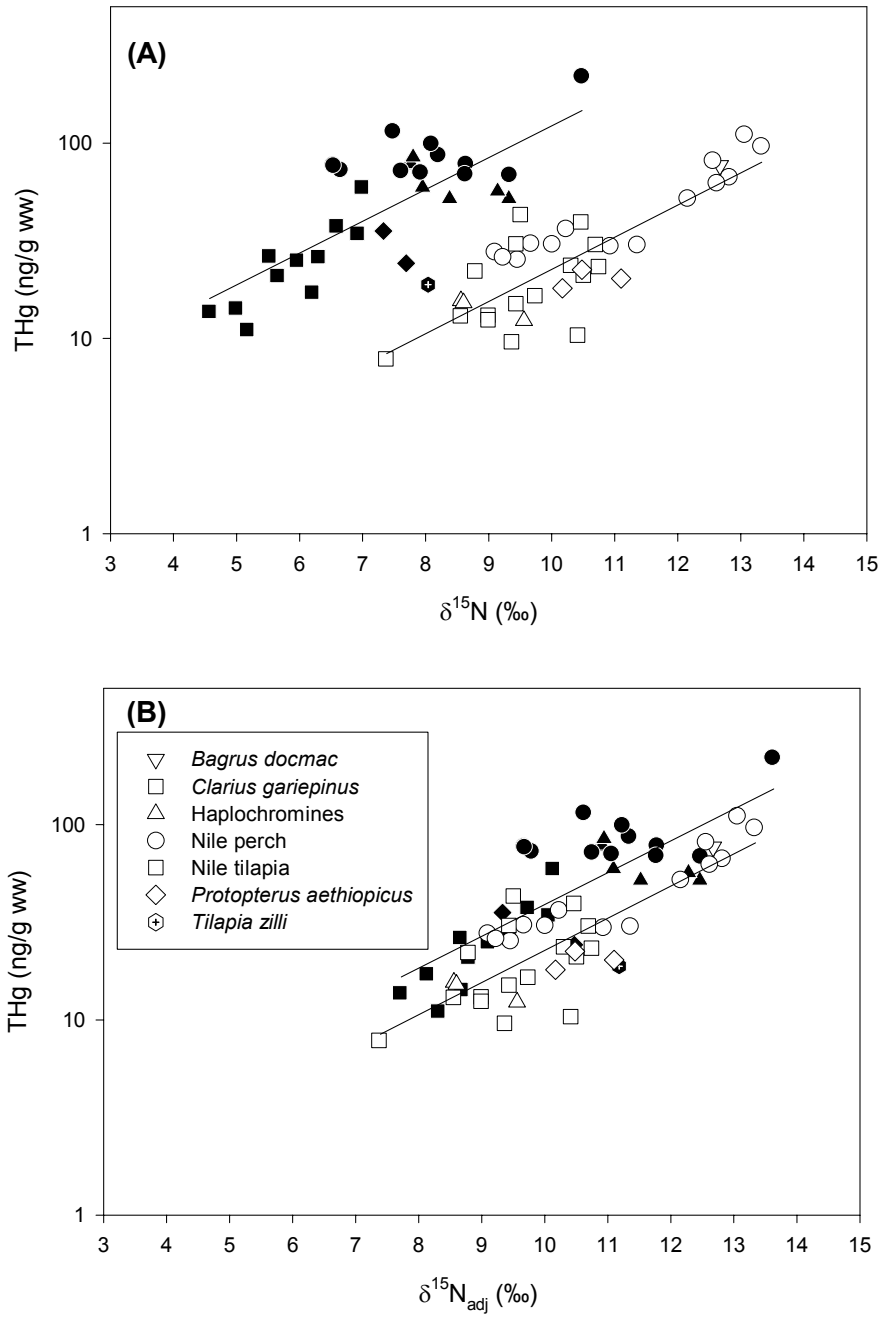
(A)
THg (ng/g ww)
100
10
1
3
4
5
6
7
8
9
10
11
12
13
14
15
δ15N (‰)
(B)
Bagrus docmac
Clarius gariepinus
Haplochromines
Nile perch
Nile tilapia
Protopterus aethiopicus
Tilapia zilli
THg (ng/g ww)
100
10
1
3
4
5
6
7
8
9
10
11
12
13
14
15
δ15Nadj (‰)

Figure 3.