J. Great Lakes Res. 29 (Supplement 2):283–291
Internat. Assoc. Great Lakes Res., 2003

Mercury Concentrations in Water, Sediment, and Biota from Lake Victoria, East Africa

Patricia S. Ramlal[1,*], Fred W.B. Bugenyi[2], George W. Kling[1], Jerome O. Nriagu[3], John W.M. Rudd[4], and Linda M. Campbell[5]

[1]*Department of Ecology and Evolutionary Biology*
University of Michigan
Ann Arbor, Michigan 48109

[2]*National Agricultural Research Organization*
Fisheries Research, Institute
P.O. Box 343
Jinja, Uganda

[3]*Department of Environmental and Industrial Health*
School of Public Health
University of Michigan
Ann Arbor, Michigan 48109

[4]*Canadian Department of Fisheries and Oceans*
Freshwater Institute
501 University Crescent
Winnipeg, Manitoba R3T 2N6

[5]*Canada Centre for Inland Waters*
Environment Canada
867 Lakeshore Road
Burlington, Ontario L7R 4A6

ABSTRACT. *Lake Victoria, East Africa, is the site of the world's most productive freshwater fishery. Mercury in muscle tissue of the 2+ and 3+ year old Nile perch* (Lates niloticus), *presently the largest constituent of the fishery, was 90 to 250 ng /g wet weight. This is similar to the range of mercury in fish muscle reported for the commercial fish of the Laurentian Great Lakes (140 to 320 ng/g). The average total mercury in the water column (7.5 ng Hg/L; n = 14) was at the upper range normally defined for uncontaminated water (< 10 ng Hg/L). The average mercury concentration in the solid phase of the top 10 cm of sediments was 220 ng Hg/g close to that found in the surface sediments of the Laurentian Great Lakes. Methylmercury measured in the surface water near a variety of wetland vegetation was low with the possible exception of water collected near the roots of the water hyacinth,* Eichhornia crassipes. *Although the levels of mercury in fish are within the accepted guidelines of the FAO/WHO, the people living in the vicinity of the lake are likely to consume a greater quantity of fish than those living some distance away from the lake. It is important to educate the consumers of the fish from Lake Victoria about any potential risks and to monitor the fish mercury levels.*

INDEX WORDS: *Lake Victoria, mercury, contaminants, tropical lakes.*

[*]Corresponding author. E-mail: RamlalP@dfo-mpo.gc.ca
Current address: Canadian Department of Fisheries and Oceans, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba R3T 2N6

INTRODUCTION

Lake Victoria, East Africa, is currently the site of the world's most productive freshwater fishery with annual yields exceeding 500,000 metric tons (Ogutu-Ohwayo *et al.* 1996). There is increasing industrialization in the watershed and a large human population that relies on the fish in the lake as a primary source of animal protein. In spite of the tremendous importance of fish to the diet of the local population, as well as an export commodity, few studies have been done on measurements of mercury (Hg) in fish muscle, or of the aquatic environment of Lake Victoria in general. Ikangura and Akagi (1996) monitored fish and human exposure to Hg near the Lake Victoria gold fields in Tanzania. They found low Hg concentrations in fish (1.8 to 16.9 ng Hg/g; mean 7.0 ng Hg/g), and that gold mining had not produced a significant increase in environmental methylmercury (MeHg) concentrations. No published results were found for biota, water, or sediments collected from the northern area of the lake. With such a large population dependent upon the fish protein it is important to know what, if any, role Hg might play in the quality of the fish being consumed. Also Hg concentrations in a large tropical lake were compared to those of the North American Great Lakes.

METHODS AND MATERIALS

Lake Victoria is the second largest of the world's great lakes in terms of surface area, the largest of the African Great Lakes, and the largest eutrophic lake in the world (Hecky and Bugenyi, 1992, Hecky 1993, Hecky *et al.* 1994, Mugidde 1993). Despite the fact that it covers a vast area (68,800 km^2), Lake Victoria is relatively shallow; the maximum depth of the lake is only 69 m (Johnson *et al*. 1996) and the mean depth has been estimated to be 40 m. The pelagic euphotic zone of the lake has decreased to ~7.5 m from ~15 m in the early 1960s (Hecky 1993) and even greater changes have occurred in nearshore areas (Mugidde 1993). Water residence time in Lake Victoria is 23 years with direct precipitation and evaporation on the lake's surface dominating the water budget (Bootsma and Hecky 1993).

The study area was located mainly near Jinja on the northern shore of the lake (Fig. 1). At the time of this investigation there were no industrial sources of Hg near Jinja. However, on Napoleon Gulf there were some industries including a fish processing plant and tannery. In the past a copper mine and processor had been located in the vicinity

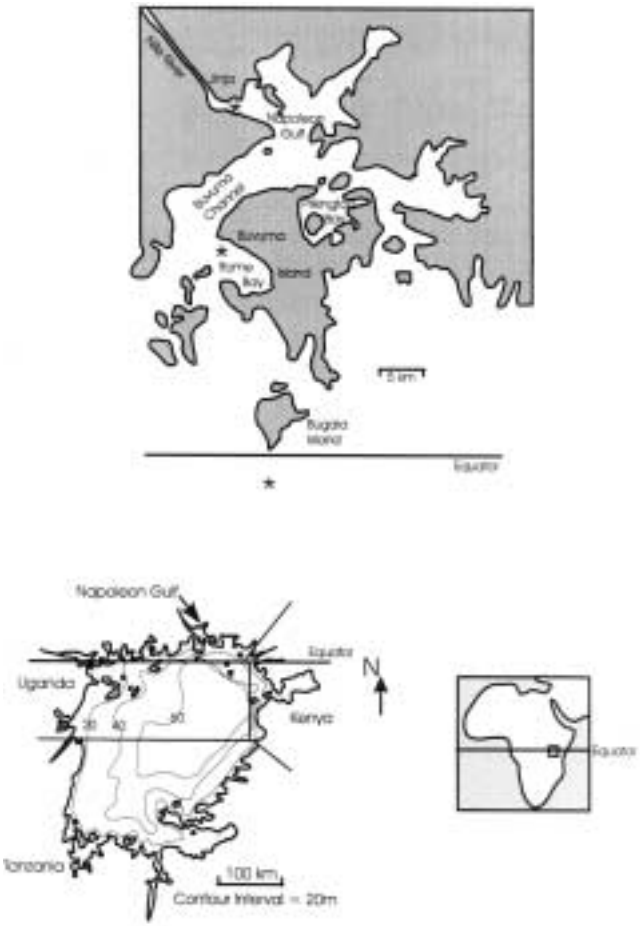

FIG. 1. Location of northern sampling sites in Lake Victoria.

of Napoleon Gulf. There is also a great deal of biomass burning that occurs around the shoreline. Biomass burning is used as an agricultural practice to promote the productivity of grazing land, to clear land for cultivation, and required in the production and use of charcoal. Nriagu (1992) estimated that 300 metric tons of Hg are emitted via burning of forests and savannas on the African continent every year.

The collection sites of water for MeHg determination were mainly from the surface water of marginal wetlands near a variety of macrophyte types. These included *Phragmites* (reeds), *Cyperus* (papyrus), *Vossia* (hippo grass), and *Eichhornia crassipes* (water hyacinth). The outflow of a stream in Napoleon Gulf and the open water in Napoleon Gulf (Fig. 1) were also sampled. Water profiles were collected from a deep (66 m) offshore station near Bugaia Island and in Napoleon Gulf near the city of Jinja (Fig. 1). Sediment cores were collected

from Itome Bay near Buvuma Channel (Fig. 1) from a water depth of 25 m. Johnson *et al.* (1998) provided material from an offshore ^{14}C-dated piston core collected where the depth of the overlying water was ~ 68 m (V96-5MCA; 1° 40.4′S; 33° 9.1′E) for total mercury analysis. Fish and other biota were collected from Napoleon Gulf and near Bugaia Island.

Water sample bottles were cleaned and prepared as described in St. Louis *et al.* (1994) and their protocol for the "clean hands, dirty hands" technique was followed. Surface water for analysis of MeHg was collected in 125-mL Teflon bottles, kept dark and cool, and transported to North America within a few days of collection. Unfiltered MeHg samples were analyzed according to the procedure of Bloom (1989). The detection limit of this method is 0.01 to 0.02 ng Hg/L at a blank level of 0.05 to 0.1 ng Hg/L. The blank level in the samples was 0.03 ng Hg/L. Water for total Hg (THg) analysis was collected also using the "clean hands, dirty hands" technique, preserved with trace metal grade 6N HNO_3, and analyzed within a few days to a few weeks of transport to North America. Water was analyzed according to the methods of Bloom and Crecelius (1983). Profiles of dissolved oxygen (mg/L) were measured with a Hydrolab Surveyor II, cross-calibrated with Winkler titrations.

Sediment cores were collected from Itome Bay using a KB corer. These cores were sectioned at the laboratory in Jinja and frozen until the time of their analysis. One of the cores was dated using ^{210}Pb analysis (Oldfield and Appleby 1984, Robbins 1978) at the Freshwater Institute (FWI; Winnipeg, Manitoba, Canada). Another was sent to the University of Michigan (Ann Arbor, Michigan, USA) for analysis of mercury in the solid phase. For comparative purposes the V96-5MC core, taken in 1996 by Johnson *et al.* (1998) near the middle of the lake, was also analyzed for total Hg in the solid phase at the University of Waterloo.

For this study most of the measurements of mercury in fish were done on the Nile perch (*Lates niloticus*). These fish are the most successful predator and in the waters of Lake Victoria and can reach sizes greater than 100 kg, although most of the fish harvested are between 2 to 4 kg at ages 2+ or 3+ years (Kitchell *et al.* 1997). The other major components of the fishery are the Nile tilapia (*Oreochromis niloticus*) and a small zooplanktivorous cyprinid *Rastrineobola argentae* (Ogutu-Ohwayo 1994). The fish were collected by trawl from the R/V *Ibis*. Other fish collected for analysis include *Brycynus* sp. and some small haplochromines. Tissue samples from behind the dorsal fin were excised, air-dried and kept in glass or plastic vials until their return to North America. Whole bodies of *R. argentae*, and the shrimp *Caridina nilotica* were dried and kept in foil or plastic until the time of analysis. Nile perch collected in February 1995 were analyzed at the FWI following the methods of Hendzel and Jamieson (1976). Subsequent collections of biota were analyzed at the University of Michigan using microwave digestion methods and nondispersive atomic fluorescence spectrometry (Bloom and Fitzgerald 1988).

Measurements of THg on biological material were made using dried materials. A correction factor of 0.31 dry:wet weight was applied to the fish samples because generally only wet weights were available. This correction was determined using the weights of five Nile perch of various sizes before and after drying the entire fish and the mean ratio was 0.311 ± 0.004 dry:wet weight. Fish were dried at 60°C until a constant weight was reached. These estimates of dry:wet weight are similar to others measured on Lake Victoria Nile perch (P.N. Reinthal, pers. comm.).

RESULTS AND DISCUSSION

THg in water profiles ranged from 3 to 15 ng/L (Fig. 2). The highest concentration, 15.5 ng Hg/L, occurred at 40 m depth. THg in Napoleon Gulf averaged 3.2 ng/L at 1 m and 4.1 ng/L at 13 m. These concentrations are above what would be expected in uncontaminated water. For example Mason and Sullivan (1997) measured average THg concentrations of 0.32 ng/L in Lake Michigan waters. The sulfate concentration in the Bugaia profile ranged from 13 to 16 µM (unpublished results). The bottom waters at Bugaia were becoming anoxic by late October 1995 when the concentration of oxygen was < 2 mg/L below 40 m (Fig. 2). By late December the water below 40 m was completely anoxic.

Levels of MeHg observed in the surface waters of Napoleon Gulf were often low (Table 1); in some cases the concentration was less than 2 times that of the distillation blank (0.031 ng Hg as MeHg/L). These values are higher than would be expected in remote systems (Lucotte *et al.* 1999), but lower than would be expected in wetlands (St. Louis *et al.* 1994). Lucotte *et al.* (1999) measured an average MeHg concentration of 0.049 ng/L (range 0.018 to 0.115;n = 30) for several remote lakes of northern Quebec. The low concentration of MeHg found in

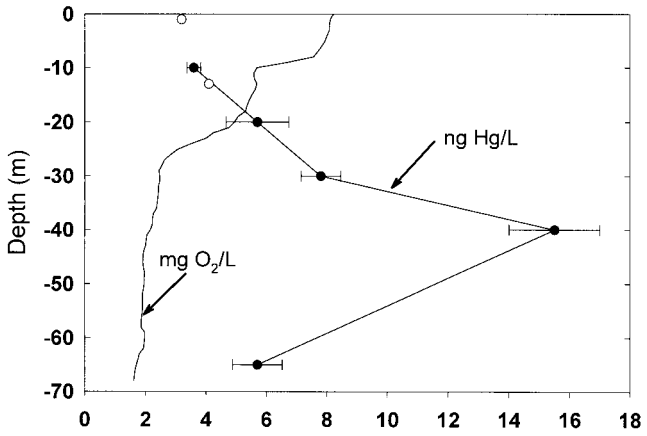

FIG. 2. Oxygen and total mercury profile (filled circles) from Bugaia sampling station. Samples collected at Bugaia 21 October 1995. Oxygen measurements taken at 1 m intervals. Mercury results are an average of 3 replicates; error bars indicate the standard error about the mean. Two samples for total mercury from Napoleon Gulf (open circles) were taken on 2 November 1995.

these waters was unexpected because wetlands are often considered to be a source of MeHg to aquatic systems although these are generally sphagnum wetlands of the temperate and subarctic climates (St. Louis *et al*. 1994). The mean MeHg concentration for all sites monitored in Napoleon Gulf was 0.096 ± 0.026 ng/L. There may be some indication of higher MeHg concentration in the water found near the roots of the water hyacinth (0.141 ng Hg as MeHg/L) but more measurements in and around the water hyacinth are necessary to determine if this value is statistically different from the other values. It may be necessary to sample the biota associated with water hyacinth that are frequently found near the root system of the floating mat (*Caridina nilotica*, juvenile Nile perch, etc.).

TABLE 1. Results of methylmercury survey, Napoleon Gulf (Lake Victoria), 2 November 1995.

Site in Napoleon Gulf	Net MeHg as Hg ng/L
Deionized water blank	0.031
Distillation blank	0.028
Open water (rep 1)	0.071
Open water (rep 2)	0.133
Open water	0.064
Water near *Eichhornia crassipes*	0.141
Water near *Vossia*	0.108
Water near *Cyperus*	0.106
Water near *Phragmites*	0.083
Stream	0.072
Stream	0.082

It is presently unclear why the measured MeHg concentrations in the water were so low. Lake Victoria has among the lowest sulfate concentrations of any lake in the world, ~ 15 µM (Giblin *et al.* 1996, Hesse 1957, this study). However, net sulfate reduction was low to almost undetectable in the surface sediments of cores collected from inshore and offshore sites (unpublished data). Although sulfate-reducing bacteria are believed to be the major bacterial group responsible for MeHg production in aquatic systems (Gilmour and Henry 1991), sulfate reducers can be active and methylate mercury in the absence of sulfate.

One of the cores taken at Itome Bay was dated using excess ^{210}Pb accumulation in the sediments (Fig. 3). Based on the theoretical ^{210}Pb flux the current sedimentation rate was calculated as 276 g/m^2/y. This inshore rate is considerably higher than the estimated sedimentation rate (90 to 110 g/m^2/y) of a core taken off the western shore of Lake Victoria near Kisumu with an overlying water depth of 55 m (Hecky 1993, Lipiatou *et al*.1996).

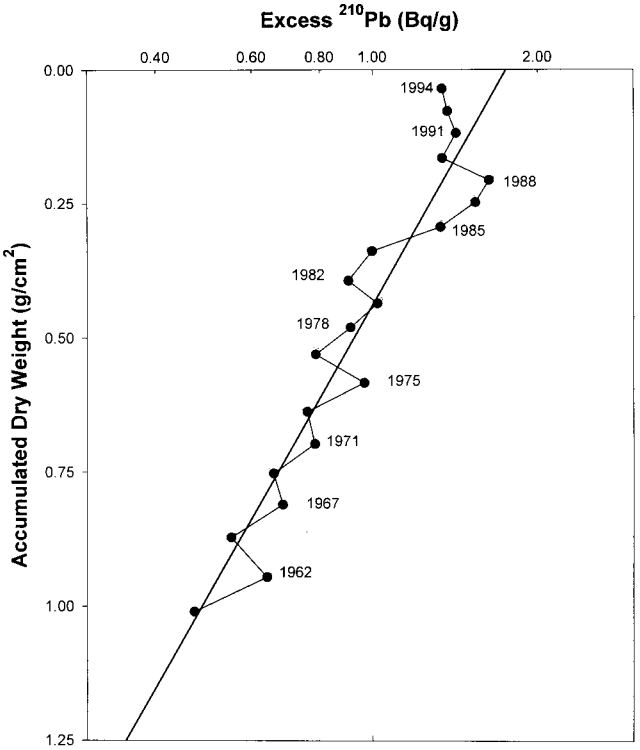

FIG. 3. Excess ^{210}Pb accumulation in the Itome Bay sediments (r^2 = 0.84). Sedimentation rate is 276 g/m^2/y. Theoretical ^{210}Pb flux is 438 Bq/m^2/y.

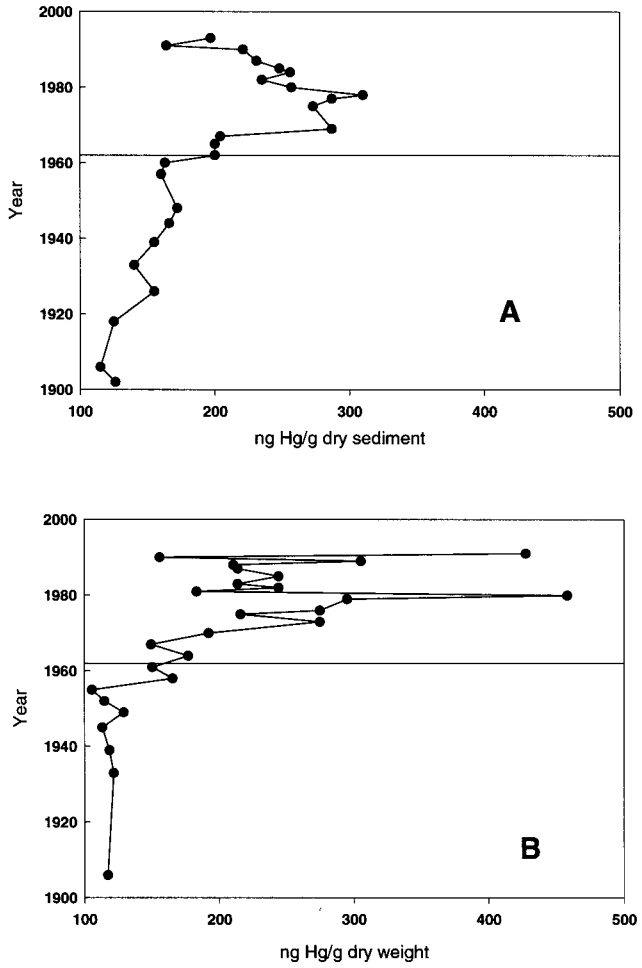

FIG. 4. A. Total mercury profile in the solid phase of the core taken from Itome Bay, 9 October 1995. B. Total mercury profile in the solid phase of the core, 5MCA, taken offshore (1° 40.4′S; 33° 9.1′E), 1996. The horizontal line at 1962 indicates the year of the > 2 m rise in lake level.

There was an apparent increase in the THg in the solid phase after ~1962 in both Itome Bay (Fig. 4A) and in the offshore core of Johnson *et al*. (1998) (Fig. 4B). In a survey of the available African literature Nriagu (1992) suggested a baseline value for Hg in sediments as 40 ng Hg/g, and found that the concentration in aquatic African sediments ranged from 50 to 2,200 ng Hg/g. The recently deposited sediments in Itome Bay (0 to 10 cm, ~15 years) had an average concentration of 220 ng Hg/g, above the baseline value, but near the lower end of the range found by Nriagu (1992). Additionally, the recent sediments of the offshore core, V96-MCA, show a similar trend of increased deposition since the mid 1960s (Fig. 4B). The range of Hg in the surface sediments of Lake Michigan was 30 to 380 ng/g, and Lake Superior was 94 to 160 ng/g (Mudroch *et al*. 1988). Matty and Long (1995) examined the early diagenesis of Hg in the sediments of Lakes Michigan and Superior. They found a mercury concentration gradient that suggested diffusive flux of Hg to the overlying lake water. This is also possibly occuring in Lake Victoria.

Soil erosion from shorelines may account for the rise in Hg since 1960. The normal seasonal change in lake level is 0.2 to 0.4 m but in 1962 there was a > 2 m increase in lake level (Beadle 1981). This > 2 m increase in lake level caused disturbance in the watershed and may be the cause of the increased Hg reflected in the mercury chemistry profiles of the cores (Fig. 4). The results show a peak in the concentration of Hg in the sediments following the early 1960s. This high lake level may be analogous to the increase of lake levels after river impoundment for hydroelectric development. Following the construction of reservoirs which lead to the inundation of terrestrial material it has been shown that the concentration of Hg in the tissue of fish increased dramatically above pre-flooding levels. This increase was attributed to the release and increased mobility of Hg previously sequestered in soil and lake sediments (Bodaly *et al*. 1984, Hecky *et al*.1992). In a study of tropical ecosystems Burger (1997) suggested that the high mercury values of the cattle egret from the Aswan, which feeds on insects, may be due to the recent flooding which could affect the Hg levels in the entire ecosystem. She further suggests that flooding of tropical soils may result in higher Hg concentration because of the rapidity with which organic matter is produced and cycled through the ecosystem. Other possible explanations for the increase in Hg in the sediments besides, or in addition to, the lake level rise may be: (1) a change in land use, particularly in biomass burning; (2) a localized increase in population or industry; or (3) a global increase in baseline Hg concentration (Fitzgerald *et al*. 1998, Lockhart *et al*. 1998). Lucotte *et al*. (1999), among others, has demonstrated that significant amounts of anthropogenic Hg can be transported long distances before deposition. Given that the profiles of total Hg in the solid phase of both of the cores are similar in magnitude, the latter explanation also seems feasible.

The Nile perch, a piscivore, had substantially higher Hg concentrations than did any of the other biota sampled (Table 2), ranging from 293 to 812

TABLE 2. Total mercury concentration in the tissue of* Lates niloticus *and* Oreochromis niloticus *and whole bodies of other biota.

Species	Date sampled	Location	Length cm	Wet Wgt. g	Mean Hg ng/g dry wgt.
Lates niloticus	08-Feb-95	Nap. G.	23	116	439
Lates niloticus	08-Feb-95	Nap. G.	24	142	409
Lates niloticus	08-Feb-95	Nap. G.	24	142	369
Lates niloticus	08-Feb-95	Nap. G.	29	275	617
Lates niloticus	08-Feb-95	Nap. G.	48	1,400	344
Lates niloticus	08-Feb-95	Nap. G.	55	1,950	536
Lates niloticus (rep 1)	08-Feb-95	Nap. G.	71	4,500	605
Lates niloticus (rep 2)	08-Feb-95	Nap. G.	71	4,500	812
Lates niloticus	30-May-95	Nap. G.	39.5	710	495
Lates niloticus	30-May-95	Nap. G.	39	715	345
Lates niloticus	30-May-95	Nap. G.	40	780	394
Lates niloticus	30-May-95	Nap. G.	44	1,000	792
Lates niloticus	30-May-95	Nap. G.	43	955	536
Lates niloticus	19-Oct-95	Nap. G.	47.5	1,250	382
Lates niloticus	19-Oct-95	Nap. G.	53.5	1,900	371
Lates niloticus	19-Oct-95	Nap. G.	39.6	750	314
Lates niloticus	19-Oct-95	Nap. G.	30.5	330	306
Lates niloticus	19-Oct-95	Nap. G.	24	155	370
Lates niloticus	19-Oct-95	Nap. G.	23	135	326
Lates niloticus	19-Oct-95	Nap. G.	17.9	55	359
Lates niloticus	19-Oct-95	Nap. G.	13.8	30	343
Lates niloticus	19-Oct-95	Nap. G.	10.5	9	293
Brycynus sp.	19-Oct-95	Bugaia	9	4	81.2
Rastrineobola argentae	19-Oct-95	Bugaia			87.3
Haplochromine sp.	19-Oct-95	Bugaia			81
Oreochromis niloticus	19-Oct-95	Nap. G.	35	1,155	34.6
Oreochromis niloticus	19-Oct-95	Nap. G.	21.3	200	49.9
Oreochromis niloticus	19-Oct-95	Nap. G.	15.9	80	110
Caridina nilotica (0 m)	25-Oct-95	Nap. G.			87.3
Caridina nilotica (5 m)	26-Oct-95	Nap. G.			115

ng Hg/g dry weight. Other fish had much lower Hg concentrations, 35 to 110 ng Hg/g dry weight. Although there were only three samples of the Nile tilapia it was interesting to note that as the size of the fish increased from 80 to 1,155 g wet weight there was less Hg in the fish muscle.

When the fish Hg data were corrected for wet to dry weight differences and plotted against the wet weight (Fig. 5) there was only a slight relationship between size and Hg content. The Hg concentrations ranged from 90 to 250 ng/g for Nile perch and from 11 to 34 ng/g for Nile tilapia. The slope of the least squares regression of log Hg (ng Hg/g wet weight) on log wet weight is statistically different from zero at a significance level of $P = 0.011$. However this relationship is weak compared to other published results (Scott and Armstrong 1972). This is not too surprising because although the weight range is broad it encompasses only 2-year classes. A relationship with Hg and fish weight would be expected only over a much larger age range.

The question still to be considered is "How is it possible to account for the amount of Hg found in the fish?" Using an average sediment mercury concentration of 250 ng/g dry weight and annual sediment deposition rate of 276 $g/m^2/y$, an annual deposition of 69 $\mu g\ Hg/m^2/y$ would be expected. In Lake Michigan, Mason and Sullivan (1997) determined that about 40% of the Hg at the sediment water interface was recycled. If a similar calculation is applied to the Lake Victoria situation about 50% of the recently deposited Hg may be recycled.

As population and industrial growth continues it will become even more important to monitor the levels of pollutants in the food and water of the people living around Lake Victoria. Nriagu (1992) found emission guidelines were seldom followed (Semu *et al*. 1986) by industries responsible for

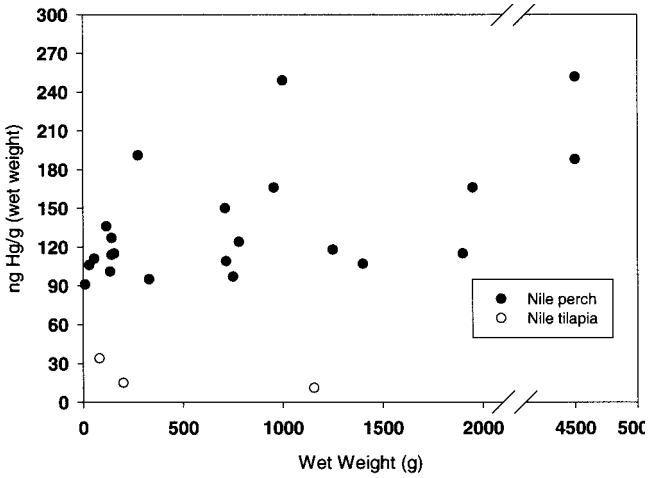

FIG. 5. Mercury concentration in fish muscle (wet weight). Wet weight calculations were based on a factor of 0.31 dry: wet weight. Closed circles are Nile perch and open circles are Nile tilapia. Fish were collected in February, May, and October 1995.

producing or discharging pollutants. In 1992 Nriagu wrote a review of toxic metal pollution in Africa describing the increase in lead pollution from automobiles and cottage industries. Lead contamination in the water could also be indicative of an associated mercury problem. Globally, fossil fuel burning is the second largest anthropogenic source of mercury (22%) following final consumption of manufactured goods (60%) (Matheson 1979). Almost all of the mercury released from fossil fuels is emitted as vapor during the burning of those fuels. However, Lipiatou *et al.* (1996) measured polycyclic aromatic hydrocarbons (PAH) in an offshore core from Lake Victoria. The PAH concentrations increased to the surface of the core, likely a consequence of increased biomass burning as human population has increased. The dominant PAH were originating from low temperature combustion and wood burning.

While the levels of mercury of fish in Lake Victoria are currently within the acceptable limits for international markets (500 ng/g in Canada; 1,000 ng/g in the USA) it important to keep in mind that for many people living in the region, fish is the major source of animal protein. An individual living close to the lake is likely to consume more fish than is dictated by the U.S. Food and Drug Administration (FDA) which suggests limits of consumption for fish containing 500 ppb mercury. These limits are based on a weekly fish consumption rate of 400 g/person or a monthly limit of 400 g/person for infants and women of child-bearing age. FAO/WHO estimated a permissible tolerable weekly intake of MeHg of 3.3 µg Hg/ kg/week; a 62 kg adult is permitted 19 µg Hg/day (Bernier *et al.* 1995). However, Rice (1995), using an estimate of daily fish consumption by Canadians of 20 g, suggested that a 62 kg woman should not consume more than 4 µg Hg/day. Using this daily estimate of 20 g/day the maximum allowable level in fish is 300 ng/g. Rice (1995) concluded that offspring of women consuming large quantities of fish (> 40 g fish/day) were at risk. The concentration of Hg in commercial fish in the North American Great Lakes, excluding Lake Michigan, was 140 to 320 ng/g (Bernier *et al.* 1995); similar to values found in the Nile perch of Lake Victoria. These levels of Hg concentration in fish muscle have triggered health advisories against high rates of consumption in the North American Great Lakes.

Mercury concentrations in the water column in Lake Victoria are higher than would be found in uncontaminated lakes and the concentrations in the solid phase of the sediments and the fish are comparable to those of the North American Great Lakes. It is important that riparian consumers of fish from Lake Victoria are educated about any potential hazards and the concentration of mercury in fish should be monitored.

ACKNOWLEDGMENTS

We are grateful to the Government of the Republic of Uganda for giving us permission to work on Lake Victoria. J. Balirwa, T. Bridgeman, R. Hecky, R. Ogutu-Ohwayo, and T. Twongo provoked thoughtful discussion of the manuscript. Reviews by R. Allen and R.A. Bodaly considerably improved the manuscript. We thank the following for their assistance in collecting and analyzing data for this paper: the crew of the R/V *Ibis*, Peter Nyonyintono and Rose Mugidde at the Fisheries Research Institute (FIRI) in Jinja, and J.F. Kitchell and D.E. Schindler of the University of Wisconsin all helped with the sampling and logistics; the Analytical Chemistry unit of the Freshwater Institute (FWI) in Winnipeg, Paul Wilkinson of the FWI for running the core dating analyses. K. Ramlal ran fish mercury analyses at FWI. Anne Giblin was responsible for chemical analyses of cores at MBL. The School of Public Health, University of Michigan, was responsible for core and fish mercury analyses. This

work was supported in part by NSF grants DEB 931808 and DEB 9553064 to GWK.

REFERENCES

Beadle, L.C. 1981. *The inland waters of tropical Africa. An introduction to tropical limnology*. 2nd edition. London: Longman.

Bernier, J., Brousseau, P., Krzystyniak, K., Tryphonas, H., and Fournier, M. 1995. Immunotoxicity of heavy metals in relation to Great Lakes. *Environ. Health. Perspec. Suppl*. 9.103:23–34.

Bloom, N.S. 1989. Determination of picogram levels of methylmercury by aqueous phase ethylation, followed by cryogenic gas chromatography with cold vapour atomic fluorescence detection. *Can. J. Fish. Aquat. Sci*. 46:1010–1017.

_____, and Crecelius, E.E. 1983. Determination of mercury in seawater at subnanogram per liter levels. *Mar. Chem.* 14:49–59.

_____, and Fitzgerald, W.F. 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.

Bodaly, R.A., Hecky, R.E., and Fudge, R.J.P. 1984. Increases in fish mercury levels in lakes flooded by the Churchill River diversion, northern Manitoba. *Can. J. Fish. Aquat. Sci.* 41:682–694.

Bootsma, H.A., and Hecky, R.E. 1993. Conservation of the African Great Lakes: a limnological perspective. *Conservation Biology* 7:644–656.

Burger, J. 1997. Ecological effects and biomonitoring for mercury in tropical ecosystems. *Water, Air, and Soil Pollution* 97:265–272.

Fitzgerald, W.F., Engstrom, D.R., Mason, R.P., Nater, E.A. 1998. The case for atmospheric mercury contamination in remote areas. *Environ. Sci. Technol.* 32:1–7.

Giblin, A., Bugenyi, F., Kling, G., Ramlal, P., Magumba, M. 1996. Respiration and nutrient release from Lake Victoria sediments: effects of anoxia and added sulfate concentrations. *American Society of Limnology and Oceanography, National Meeting,* 16–20 June 1996, Milwaukee, Wisconsin.

Gilmour, C.C., and Henry, E.A. 1991. Mercury methylation in aquatic systems affected by acid deposition. *Environ. Pollut.* 71:131–169.

Hecky, R.E. 1993. The eutrophication of Lake Victoria. *Verh. Internat. Verein. Limnol*. 25:39–48.

_____, and Bugenyi, F.W.B. 1992. Hydrology and chemistry of the African Great Lakes and water quality issues: Problems and solutions. *Mitt. Int. Verein. Limnol*. 23:45–54.

_____, Ramsey, D.J., Bodaly, R.A., and Strange, N.E. 1992. Increased methylmercury contamination in fish in newly formed freshwater reservoirs. In *Advances in Mercury Toxicology,* eds. T. Clarkson and T. Sukuki. New York: Plenum.

_____, Bugenyi, F.W.B., Ochumba, P., Talling, J.F., Mugidde, R., Gophen, M., and Kaufman, L. 1994. Deoxygenation of the deep water of Lake Victoria, East Africa. *Limnol. Oceanogr.* 39:1476–1481.

Hendzel, M.R., and Jamieson, D.M. 1976. Determination of mercury in fish. *Anal. Chem.* 48:926–928.

Hesse, P.R. 1957. The distribution of sulphur in the muds, water and vegetation of Lake Victoria. *Hydrobiologia* 11:29–39.

Ikangura, 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. Total Environ.* 191:59–68.

Johnson, T.C., Scholz, C.A, Talbot, M.R, Kelts, K., Ricketts, R.D., Ngobi, G., Beuning, K., Ssemmanda, I., and McGill, J.W. 1996. Late Pleistocene desiccation of Lake Victoria and rapid evolution of Cichlid fishes. *Science* 273:1091–1093.

_____, Chan, Y., Beuning, K., Kelts, K., Ngobi, G., and Vershuren, D. 1998. Biogenic silica profiles in Holocene cores from Lake Victoria: implications for lake level history and initiation of the Victoria Nile. In *Environmental Change and Response in East African Lakes,* ed. J.T. Lehman, pp. 75–88. Dordrecht, Netherlands: Kluwer Academic Publishers.

Kitchell, J.F., Schindler, D.E., Ogutu-Ohwayo, R., and Reinthal, P.N. 1997. The Nile perch in Lake Victoria: interactions between predation and fisheries. *Ecol. Appl.* 7:653–664.

Lipiatou, E., Eisenreich, S.J., Hecky, R.E., Lockhart, L., Muir, D., and Wilkinson, P. 1996. Recent ecosystem changes in Lake Victoria reflected in sedimentary natural and anthropogenic organic compounds. In *The limnology, climatology, and paleoclimatology of the East African lakes,* eds. T.C. Johnson and E.O. Odada, pp. 523–541. Amsterdam: Gordon and Breach Publ.

Lockhart, W.L., Wilkinson, P., Billeck, B.N., Danell, R.A., Hunt, R.V., Brunskill, G.J., Delaronde, J., and St. Louis, V. 1998. Fluxes of mercury to lake sediments in central and northern Canada inferred from dated sediment cores. *Biogeochemistry* 40:163–173.

Lucotte, M., Montgomery, S., Caron, B., and Kainz, M. 1999. Chapter 3: Mercury in natural lakes and unperturbed terrestrial ecosystems of Northern Quebec. In *Mercury in the Biogeochemical Cycle,* eds. M. Lucotte, R. Schetagne, N. Therien, C. Langlois, and A. Tremblay, pp. 55–87. Berlin: Springer-Verlag.

Mason, R.P., and Sullivan, K.A. 1997. Mercury in Lake Michigan. *Environ. Sci. Technol.* 31:942–947.

Matheson, D.H. 1979. Mercury in the atmosphere and in precipitation. In *The biogeochemistry of mercury in the environment,* ed. J.O. Nriagu, pp. 113–129. Amsterdam: Elsevier/North-Holland Biomedical Press.

Matty, J.M., and Long, D.T. 1995. Early diagenesis of

mercury in the Laurentian Great Lakes. *J. Great Lakes Res.* 21:574–586.

Mudroch, A., Srazin, 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.

Mugidde, R. 1993. The increase in phytoplankton primary productivity and biomass in Lake Victoria (Uganda). *Verh. Internat. Verein. Limnol.* 25:846–849.

Nriagu, J.O. 1992. Toxic metal pollution in Africa. *Sci. Total Environ.* 121:1–37.

Ogutu-Ohwayo, R. 1994. Adjustments in fish stocks and in life history characteristics of the Nile perch, *Lates niloticus* L., in lakes Victoria, Kyoga, and Nabugabo. Ph.D. thesis (Zoology), University of Manitoba. Winnipeg, Manitoba, Canada.

_____, Hecky, R.E., Bugenyi, F.W.B., Mugidde, R., Ndawula, L., Mbahinzireki, G., and Wandera, S.B. 1996. Some causes and consequences of rapid ecosystem changes in a large tropical lake—Lake Victoria. In *Proc. Joint Vic Falls conference on aquatic systems and international symposium on exploring the Great Lakes of the world (GLOW), food-web dynamics, health and integrity.* Victoria Falls, Zimbabwe. 15–19 July 1996.

Oldfield, F., and Appleby, P.G. 1984. Empirical testing of Pb-210 dating models for lake sediments. In *Lake sediments and environmental history,* eds. E.V. Howath and J.W.G. Lund. Minneapolis: University of Minnesota Press.

Rice, D.C. 1995. Neurotoxicity of lead, methylmercury, and PCBs in relation to the Great Lakes. *Environ. Health Perspec. Suppl.* 9.103:71–87.

Robbins, J.A. 1978. Geochemical and geophysical applications of radioactive lead. In *The biogeochemistry of lead in the environment, Part A,* ed. J.O. Nriagu, pp. 285–393. Amsterdam: Elsevier/North Holland Biomedical Press.

St. Louis, V.L., Rudd, J.W.M., Kelly, C.A., Beaty, K.G., Bloom, N.S., and Flett, R.J. 1994. Importance of wetlands as sources of methyl mercury to boreal forest ecosystems. *Can. J. Fish. Aquat. Sci.* 51:1065–1076.

Scott, D.P., and Armstrong, F.A.J. 1972. Mercury concentration in relation to size in several species of freshwater fishes from Manitoba and northwestern Ontario. *J. Fish. Res. Board Can.* 29:1685–1690.

Semu, E., Singh, B.R., and Selmer-Olsen, A.R. 1986. Mercury pollution of effluent, air, and soil near a battery factory in Tanzania. *Water, Air, and Soil Pollution* 27:141–146.

Submitted: 18 July 2000
Accepted: 14 December 2002