Post-Impoundment Increases in Fish Mercury Levels in the Southern Indian Lake Reservoir, Manitoba

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ABSTRACT

Bodaly, R. A., and R. E. Hecky. 1979. Post-impoundment increases in fish mercury levels in the Southern Indian Lake reservoir, Manitoba. Can. Fish. Mar. Serv. MS Rep. 1531: iv + 15 p.

White muscle mercury levels were determined for lake whitefish from two regions of Southern Indian Lake and from Issett Lake in 1975, prior to hydroelectric diversion and impoundment, and in 1978, after diversion and impoundment. Mercury concentrations increased significantly in all three areas sampled. Mercury levels in northern pike sampled from Southern Indian Lake commercial catches also have increased since impoundment. Total mercury concentrations in water samples taken from Southern Indian Lake in 1978 were less than 0.01 $\mu g\ L^{-1}$. Methyl mercury concentrations in water samples were also very low. Bank materials which are now a major source of turbidity to the lake were likewise consistently low in mercury. It is hypothesized that leaching of soils and shoreline erosion after impoundment may generally lead to increased fish mercury concentrations in new reservoirs.

Key words: mercury compounds; freshwater fish; commercial species; sediment analysis; water analysis (chemical); reservoirs (water); freshwater lakes; selenium.

RESUME

Bodaly, R. A., and R. E. Hecky. 1979. Post-impoundment increases in fish mercury levels in the Southern Indian Lake reservoir, Manitoba. Can. Fish. Mar. Serv. MS Rep. 1531: iv + 15 p.

Les concentrations de mercure dans les muscles blancs de grands corégones provenant du Isset Lake et de deux régions du Southern Indian Lake ont été determinées en 1975 et 1978, avant et après, respectivement, la dérivation et la création d'un réservoir lors de l'aménagement hydro-électrique. Les concentrations ont augmenté de beaucoup aux trois endroits. Elles ont également augmenté chez le grand brochet dans des échantillons des prises commerciales du Southern Indian Lake, depuis la création du lac de barrage. Dans des échantillons d'eau prélevés dans ce lac en 1978, les concentrations du mercure total étaient inférieures à 0.01 $\mu g\ L^{-1}$. Les concentrations de méthyl-mercure dans les échantillons d'eau étaient également très faibles. Les matières du talus qui sont maintenant une source majeure de turbidité dans le lac contenaient également, de façon constante, peu de mercure. Les auteurs émettent l'hypothèse que le lessivage des sols et l'érosion des rives après la création des réservoirs peuvent généralement entraîner une augmentation des concentrations de mercure dans le poisson.

Mots-clés: composés du mercure; poisson d'eau douce; espèce commerciale; analyse des matières en suspension; analyse (chimique) de l'eau; réservoirs (d'eau); lacs d'eau douce; sélénium.

INTRODUCTION

Increases in fish muscle mercury concentrations have generally been associated with sources of industrial effluents (for example, see Armstrong and Hamilton 1973). Recently, however, the possibility that high turbidity associated with shallow lakes can enhance bioavailability of natural mercury present in lake sediments has been suggested by Penn (1978). Penn (1978) showed that in many northern Quebec lakes, turbidity appeared to correlate better with mercury concentrations in fish than with background (sediment) mercury concentrations.

This report presents recent data on fish, water and sediment mercury concentrations from the Southern Indian Lake reservoir. The water level of Southern Indian Lake, in northern Manitoba, was raised 3 m above its long-term mean level by impoundment in 1976 to divert the Churchill River into the Nelson River basin for hydroelectric power production. Concern over the possibility of post-impoundment increases in fish mercury levels in Southern Indian Lake arose after the 1977 and 1978 closures of the commercial fisheries of Notigi, Rat, Mynarski, Wapisu and Issett Lakes (Fig. 1) due to observed high mercury concentrations in fish. These lakes in the flooded Rat River valley lying between Notigi Lake and Issett Lake and including the western two Mynarski lakes (Fig. 1) have been joined at a common impounded water level by the Notigi control structure. Water levels at Notigi Lake increased by over 17 m (56 feet) by accumulation of local runoff waters between 1974 and 1976.

In 1976 this large body of stagnant water was connected to the impounded Southern Indian Lake with the initiation of the Churchill River Diversion. By 1978 the diversion was operating at its designed capacity of nearly 900 m^3 sec^{-1} (30,000 c.f.s.). The higher water levels of Southern Indian Lake have resulted in extensive and rapid wave erosion of surrounding glacio-lacustrine clays (Newbury et al. 1978), greatly increasing the concentration of these fine-grained bank materials in lake waters (Hecky and Newbury 1977). If correlations which Penn (1978) observed in northern Quebec pertain to northern Manitoba, then the increased turbidity in Southern Indian Lake could lead to increased mercury concentrations within the lake's fish populations.

MATERIALS AND METHODS

STUDY AREA

Southern Indian Lake is located in north central Manitoba (57°N; 99°W) on the Churchill River (Fig. 1). The lake is on Precambrian Shield, but bedrock is overlain by surficial deposits of glacial, glacio-fluvial and glacio-lacustrine origin, particularly varved silty clays laid down in glacial Lake Agassiz. In summer 1976, the lake level was raised 3 m above the mean level and 85% of the flow of the Churchill River through the lake began to be diverted from the Churchill River basin into the Nelson River basin through an artificial diversion channel (Fig. 1). Southern Indian Lake has a post-flooding surface area of 2530 km^2 and a post-flooding mean depth of 12 m. Two-thirds of the length of the flooded shore of the lake is unconsolidated material, subject to permafrost melting and wave erosion. Erosion rates of up to 20 m^3 of fine-grained materials per m of shore per open water season have been observed (Newbury et al. 1978). It was estimated that at least 225,000 tonnes of sediment were added to lake waters in the 1976 open water season while the lake was being flooded (Hecky and Newbury 1977).

Southern Indian Lake supports the largest commercial fishery in northern Manitoba with an annual catch of about 500,000 kg. Lake whitefish (*Coregonus clupeaformis*) comprises about 90% of the catch with most of the remainder being walleye (*Stizostedion vitreum)* and northern pike (*Esox lucius*).

Issett Lake (56°38'N; 99°08'W) was a small (area 3.7 km^2) lake at the headwaters of the Rat River (Nelson River basin) and is now the first lake on the diversion route between Southern Indian Lake and the Nelson River.

COLLECTION AND ANALYSIS OF SAMPLES

Fish

Lake whitefish were collected by graded mesh gill net gangs in July and August 1975 in Areas 2, 4 and 6 of Southern Indian Lake and Issett Lake (Fig. 1) and in September 1978 in Area 4 and the Channel, Southern Indian Lake and Issett Lake (Fig. 1). Fork length for these fish was determined to the nearest 5 mm. Fish were frozen soon after capture and were stored frozen at -40°C until examination in January 1979.

Specimens of walleye and northern pike were taken from commercial catches from time to time over the period 1971 to 1979 from various regions of Southern Indian Lake. Lengths were not recorded for these fish. Samples were frozen soon after capture and were analyzed in the year of capture. Mercury concentrations were determined according to Hendzel and Jamieson (1976) who report an analytical precision of ±0.025 ppm at 0.5 ppm Hg in fish muscle tissue. Log mercury concentration was regressed against log fork length and non-significant or weak correlations resulted in all samples. Therefore, simple means of mercury concentrations were compared rather than adjusting the concentrations to account for differences in size.

Water

On 26 September 1978 five samples for total mercury concentrations in water and two samples for methyl mercury concentrations in water were collected at locations indicated in Fig. 1. The sampling locations represented the full range of turbidities occurring within the reservoir with Secchi disc values from 2 m down to 0.5 m. The water samples for total mercury analyses were collected from 1 m depth using a van Dorn sampler and returned to the laboratory in 300 mL glass reagent bottles. Sample preservation, extraction and analysis followed closely that of Kopp et al. (1972). Ten liters of water were collected from the surface of the lake in a polyethylene carboy and returned to the laboratory for methyl-mercury analysis. The methyl-mercury is extracted from acidified water into benzene in a liquid-liquid extractor. Subsequent analysis follows the method of Uthe et al. (1972). The methodological precision of the total Hg analysis is ±0.010 $\mu g\ L^{-1}$ and that of the methyl-Hg analysis is ±0.002 $\mu g\ L^{-1}$.

Bank materials

Samples of eroding bank materials were collected from various locations (Fig. 1) from 1976 through 1978. In all cases samples were from fresh exposures. Subsamples were dried to constant weight at 105°C, ground in a mortar and pestle, passed through a 1.0 mm mesh screen, and then analyzed for mercury and selenium content. For mercury analysis, a weighed portion was digested with aqua regia, HNO_3:HCl (1:3), brought to a boil, simmered for one minute, cooled and made to 50 mL volume. The analysis was completed with the semi-automated procedure of Armstrong and Uthe (1971). For selenium analysis, sediment samples were digested in an aluminum block at 125°C overnight with a mixture of 4:1 nitric:perchloric acids. Ten mL of distilled water and then 7.4 mL of concentrated HCl were added sequentially. The volume of solution was made up to 25 mL with distilled water and analyzed by a modification of the method of Vijan and Wood (1976). The bank samples were also analyzed for organic carbon, carbonate, total nitrogen and total phosphorus concentrations using the methods for particulate phases of Stainton et al. (1977).

RESULTS

FISH

Lake whitefish white muscle mercury concentrations increased from 1975 to 1978 in both areas of Southern Indian Lake sampled and in Issett Lake (Table 1). Mean mercury concentrations in lake whitefish showed a significant increase from 0.05 ppm to 0.22 ppm from 1975 to 1978 in Area 4, with corresponding increases of from 0.06 ppm to 0.30 ppm in Areas 2 and 6 and from 0.15 ppm to 0.32 ppm in Issett Lake.

Mercury levels in northern pike samples taken from the commercial fishery were significantly higher after flooding (mean 0.47 ppm) as compared to before flooding (mean 0.29 ppm; Table 2). Pike mercury levels appeared to increase immediately following impoundment (Table 2). Mercury concentrations in walleye samples from the commercial fishery were not significantly different after flooding (mean 0.40 ppm) as compared to before flooding (mean 0.25 ppm) (Table 3). Despite the lack of immediate change, there was an indication of later increases in walleye mercury levels. Mean mercury concentrations in walleye in 1978 and 1979 were 0.57 and 0.53 ppm as compared to an average of D.25 ppm for 1971-1977.

WATER

Total mercury concentrations at all five stations sampled were below the limit of detection of the method used, 0.010 $\mu g\ L^{-1}$. The methyl-mercury concentration was below the detection level (0.0002 $\mu g\ L^{-1}$) in the Churchill River above Southern Indian Lake but higher, 0.0004 $\mu g\ L^{-1}$, about the dam at Notigi Reservoir through which the diverted Churchill River now flows. Because concentrations are low more intensive sampling would be required to determine if the apparent increase through the impounded waters is significant. These concentrations of total mercury and methyl-mercury are well below those reported in Clay Lake on the Wabigoon River in Northwestern Ontario which has been affected by industrial effluents (total Hg 0.01 to 0.06 $\mu g\ L^{-1}$ and methyl-Hg 0.001 to 0.003 $\mu g\ L^{-1}$ in epilimnion samples, John Rudd, personal communication).

BANK MATERIALS

Representative samples of exposed bank materials were analyzed for Hg as well as Se, total nitrogen (N), total phosphorus (P), organic carbon (C_O), and carbonate carbon (C_C) and the results are given in Table 4 along with a physical description and, for seven samples, particle size analyses. On a dry weight basis lacustrine clays tended to be richer in Hg ($\bar{x}$ = 0.010 ± 0.003 $\mu g\ g^{-1}$, n = 7) than tills ($\bar{x}$ = <0.004 $\mu g\ g^{-1}$, n = 3). These concentrations are below the range for glacial tills and clays, 0.020 to 0.100 $\mu g\ g^{-1}$, reported by Jonasson and Boyle (1971). However, we did find as did Jonasson and Boyle (1971) that Hg was enriched in the uppermost soil horizon A (Table 5). These values are in the range of soils, remote from known mercury ores, reported by Jonasson and Boyle (1971). Clearly bank materials being added to the lake are not enriched in Hg. Glacio-lacustrine clay samples BL, CH and DH from South Bay had higher Hg concentrations than clays from more northerly locations. Within the clay samples, however, there was no relationship between the percent clay and Hg concentrations. Likewise, there was no evident relationship between Hg and C_C, C_O, N or P. Armstrong et al. (1972) found significant correlations between Hg and clay content, organic carbon and total nitrogen in Clay Lake sediments.

Selenium has been shown to have ameliorative effects on the toxicity of methyl-mercury and its bioaccumulation (NRC 1978). Equimolar concentrations in tuna and swordfish have been found to significantly reduce the toxic effects of Hg (NRC 1978). Selenium concentrations in bank materials were determined (Table 4) to establish the potential availability of Se relative to Hg in the eroded material. The lowest Se:Hg ratio in bank materials was seven (Table 4) which indicates that there is potentially adequate Se in the soils to effect molar ratios which might ameliorate the effects of elevated Hg concentrations. To evaluate the possible detoxifying role of Se in Southern Indian Lake the relative concentrations of Se and Hg in the lake's biota would have to be investigated.

DISCUSSION

High concentrations of mercury in fish flesh are usually associated with intensive industrial (Bligh 1971) or agricultural (Johnels 1971) uses of the element, but high mercury concentrations in fish from lakes and reservoirs not obviously affected by technological uses of the element are known. Tam and Armstrong (1972) list a number of such lakes in which at least some sampled fish exceed 0.5 mg kg^{-1} which is the currently accepted limit for marketing in Canada. The average mercury concentrations observed in the commercial catches of pike and pickerel from Southern Indian Lake after flooding which are near the Canadian limit of acceptability are not in themselves unusual. For example, pristine Island Lake in northeastern Manitoba has 0.43 ppm Hg in its commercial catches of northern pike (Industry Services Branch data) despite being well removed from the influence of technology and being free of any hydrological manipulation.

The concentrations of Hg in Southern Indian Lake commercial catches are still well below those which led to the restriction of fishing in the lakes along the diversion route behind the Notigi Reservoir. In Rat Lake (Fig. 1) mercury concentrations exceeded 1 ppm in individual northern pike and 3 ppm in walleye (Industry Services Branch data). These concentrations are comparable to those found in fish in the lakes of the industrially polluted English-Wabigoon River System in northwestern Ontario.

Although the observed concentrations of Hg in the 1978 fish of Southern Indian Lake are not in themselves exceptional, the increases documented here are. There are no pre-impoundment Hg data for fish from the diversion route lakes which now exhibit high Hg concentrations in fish. Consequently it is not possible to determine if the high levels observed there are in any way related to the imposed hydrological changes for hydroelectric purposes. The increases in fish Hg concentrations in Southern Indian Lake are significant and seem to be associated, or at least co-occurred, with the impoundment of the lake and river diversion. Correlation or co-occurrence with an event does not necessarily imply causation. In order to find the causes of the observed changes in fish mercury concentrations, hypotheses must be formulated and tested. Our data are fragmentary; but when combined with other observations in the literature and from ongoing research, it is possible to construct a likely chain of events for Southern Indian Lake and Notigi Reservoir which could be investigated in the future. We will briefly review the observational data then formulate a hypothesis.

TURBIDITY

Penn's (1978) survey of lakes in Quebec concluded that levels of turbidity in lakes correlated with fish Hg concentrations best among the factors he considered. Likewise in Southern Indian Lake increases in fish Hg concentrations have occurred during a period in which turbidity has increased due to shoreline erosion of fine-grained permafrost-affected glacial lake sediments (Hecky and Newbury 1977; Hecky et al. 1979). In Quebec highest turbidities and Hg concentrations in fish occurred in "clay belt" lakes which have had a similar recent geological history and have a similar overburden material to Southern Indian Lake. Penn (1978) did not find a good correlation between fish Hg and Hg concentrations in parent geological material. The very low concentrations of Hg in bank materials at Southern Indian Lake likewise imply that concentration *per se* in source material is not important.

SOIL MERCURY

In northern Quebec and in Southern Indian Lake increased turbidity is a dominant factor associated with higher Hg concentrations in fish. The source of the turbidity is the same in both areas, i.e. glacio-lacustrine clay originally deposited from proglacial lakes and subsequently eroded under modern conditions. In clay soils away from significant Hg deposits, Hg exists mostly as [$HgOH^+$] and [$Hg(OH)_2$] adsorbed onto ion exchange sites of clays and onto associated hydrated oxides (Jonasson 1970). In the boreal regions of Canada humus-rich podzols form the A horizon of soils overlaying the clay subsoil. Jonasson and Boyle (1971) find Hg typically enriched in this horizon by a mean factor of 1.5-2.0 over subsoil concentrations. The mercury in these humic soils exists as Hg-humate complexes (Jonasson 1970) and the mobility is strongly pH dependent. From pH 3 to 6 the normal pH range of these podzolic soils, the Hg is strongly fixed to the humus; therefore, it tends to accumulate in this horizon. At higher pH the Hg becomes mobile and enters solution. The amount coming into solution depends on the solubility of the humic material (Jonasson 1970). Erosion of this kind of soil will release exchangeable Hg from clay particles into the water and yield dissolved Hg. Southern Indian Lake waters have pH values of 7.6-8.1 (Cleugh 1974). By cation exchange equilibrium reactions, the clay particles can yield Hg to waters which are low in Hg ion activity or take up Hg from waters with high Hg ion activity. The latter phenomenon of Hg uptake has been experimentally demonstrated at Hg polluted Clay Lake by John Rudd (personal communication).

BIOACCUMULATION

By the chain of events described above erosion of soils could lead to an increase in Hg available to biological organisms. Biological organisms have a strong affinity for Hg in solution and each transfer through the food chain tends to increase its concentrations in living tissues (Greeson 1970). Methylation by bacteria is the primary step by which Hg enters the food chain and becomes most soluble in water (Rudd et al. 1979). In addition to taking up Hg via the food chain, fish may take up methyl-mercury directly from solution via the gills (Prabhu and Hamdy 1977). Thus, the concentrations in a top predator such as a northern pike or walleye on a per unit weight basis will be much higher than in the waters from which they came. Other organisms feeding lower on the food chain, such as whitefish, will have lower concentrations but still will concentrate Hg.

Johnels (1971) gives a minimum concentration factor of 5,000 between water and pike, while Rudd (personal communication) finds the mean concentration factor in Clay Lake to be approximately 10^6 between total mercury in water and pike. If the concentration factor in Southern Indian Lake were any lower than 10^5, we would not be able to detect total mercury concentrations in the water by our methods based on the observed concentrations in fish. Therefore, the fact that our chemical analyses of Southern Indian Lake water found Hg to be indetectible certainly does not mean it was not present in amounts sufficient to account for the amounts observed in fish.

HYPOTHESIS

We postulate that: Inundation and erosion of boreal soils will generally increase the supply of Hg to a water body through leaching of the humic rich Horizon A of soils and through suspension in the water of clay particles carrying Hg as exchangeable ions. Leaching and erosion will likely increase the rate of supply of Hg to a greater extent than the measured concentration of mercury in the water because the Hg made available will rapidly enter the biota. The rate at which Hg enters the biota will be a function of the growth of methylating bacteria. The increases of Hg concentration in aquatic biota will be most prominent in the piscivorous fish at the top of the food chain. If the lake had naturally low concentrations of Hg before impoundment and the fish consequently had low Hg concentrations in their flesh, the increased supply of Hg will lead to increased concentrations of Hg in fish flesh. The increase in fish Hg concentrations after impoundment will likely be in proportion to the increase in rate of supply of Hg from leaching and erosion relative to the natural rate of supply when both rates are expressed per unit of volume per unit time. The increase may be greater than expected by this simple proportion because of the enhanced growth rates of bacteria over flooded soils and the increased primary productivity in new reservoirs may lead to higher rates of methylation.

To test this hypothesis for future application, the following could be done:

1. using Hg-203 as a radiotracer, determine the capacity of humic materials and clay minerals to take up and release Hg under variations in pH,
2. determine whether inundation of terrestrial organic material enhances the activity of methylating bacteria
3. using more sensitive analytical methods determine the natural rate of mercury supply to Southern Indian Lake and estimate the increased loading from shoreline erosion and leaching to see if the fish Hg concentrations increases are in proportion.

If increased fish Hg occurs with a high probability in new boreal reservoirs, it must be evaluated in the socio-environmental assessment of any proposed development. To date, it has not been considered.

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Table 1. Lake whitefish muscle mercury mean concentrations in different areas of Southern Indian Lake in 1975, before impoundment, and in 1978, after impoundment. Also given is the t-statistic (unequal variances) for the means. Actual fish concentrations are given in Appendix I.

Lake Region	1975 mean ppm	1978 mean ppm	t	Significance
Area 4	.05 (n = 25)	0.22 (n = 16)	7.37	$p < .05$
Areas 2 and 6	.06 (n = 50)	0.30 (n = 17)	5.93	$p < .05$
Issett Lake	.15 (n = 24)	0.32 (n = 5)	4.03	$p < .05$

Table 2. Mean mercury concentration (ppm) in northern pike from Southern Indian Lake before impoundment, 1971-1975, and after impoundment, 1976-1979. Samples were taken from the commercial fishery from various areas of the lake. Number of fish examined each year are shown.

Year	n	Average Mercury Concentration (ppm)	Pre- and Post-Impoundment Means (ppm)*
1971	4	0.26	0.29
1972	5	0.32	
1973	3	0.30	
1974	0		
1975	0		
1976	10	0.47	0.47
1977	2	0.43	
1978	7	0.50	
1979	14	0.48	

* Post-impoundment mean significantly greater than pre-impoundment mean ($F_{1\ 5}$ = 59.9; one way analysis of variance treating yearly mean concentrations as observations, before and after flooding as treatment).

Table 3. Mean mercury concentration (ppm) in walleye from Southern Indian Lake before impoundment, 1971-1975, and after impoundment, 1976-1979. Samples were taken from the commercial fishery from various areas of the lake. Number of fish examined each year are shown.

Year	n	Average Mercury Concentration (ppm)	Pre- and Post-Impoundment Means (ppm)*
1971	6	0.19	
1972	3	0.21	
1973	3	0.28	0.25
1974	0		
1975	2	0.30	
1976	4	0.24	
1977	2	0.26	
1978	7	0.57	0.40
1979	6	0.53	

* Post-impoundment mean not significantly different from pre-impoundment mean ($t_6 = 1.28$; t test with unequal variances treating yearly means as observations, before and after flooding as treatments).

Table 4. Particle size analyses, concentration of biophilic elements (C, N, P) and selenium and mercury in representative exposed bank materials from Southern Indian Lake. Carbonate carbon is C_c while C_o is organic carbon.

Sample Designation	Sampling Site Description		Weight %		C_c	C_o	N	P	Se	Hg	Se:Hg Molar
		Sand	Silt	Clay	mg g^{-1}				$\mu g\ g^{-1}$		
BL	Thick, varved clay bank; undercut and slumping	0	16	84	13	14	1.2	0.69	0.078	0.012	17
CH	Thin lacustrine clay over bedrock slope	0	49	51	36	19	1.2	0.56	0.054	0.012	11
DH	Thin lacustrine clay over gentle bedrock slope	1	34	65	20	23	0.6	0.66	0.044	0.016	7
GHE	Thin lacustrine clay over glacio-lacustrine sand dug from under peat	3	39	58	1.6	17	1.9	0.43	0.18	0.010	45
HHE 1976	Thin lacustrine clay on bedrock dug from under peat	1	34	65	2.2	20	1.7	0.68	0.099	0.008	31
HH 1978	Thin lacustrine clay on bedrock - same location as HHE from slumping face	-	-	-	34	33	1.0	0.57	0.070	0.007	25
KHE	Thin lacustrine clay over clayey fill on bedrock	9	45	46	26	22	1.4	0.58	0.10	0.006	42
GL	Thick lacustrine sand deposit, well graded	>95	tr	tr	0.4	3	1.3	0.33	0.035	<0.002	>44
Long Point	Glacial till, predominately clay; 5% cobbles	-	-	-	24	27	0.5	0.43	0.032	<0.002	>41
Kame Island	Glacial till, predominately clay; visually sandier than other tills in these samples	-	-	-	28	27	0.9	0.38	0.051	<0.002	>65
Missi Island Clay	Thin clay deposit under deep peat over bedrock	-	-	-	26	27	1.4	0.64	0.10	0.006	42
Missi Island Till	Glacial till under clay veneer over bedrock	-	-	-	24	22	0.1	0.40	0.044	0.008	14

Table 5. Mercury and selenium concentrations in soil profiles from two sites on Southern Indian Lake.

Location	Horizon	Depth	Hg	Se
		cm	$\mu g\ g^{-1}$	
HH	A	2	0.09	0.26
	C	40	0.02	0.10
	C	200	0.01	0.06
DH	A	2	0.46	0.46
	C	5	0.02	0.20
	C	15	0.03	0.18
	C	30	0.02	0.04

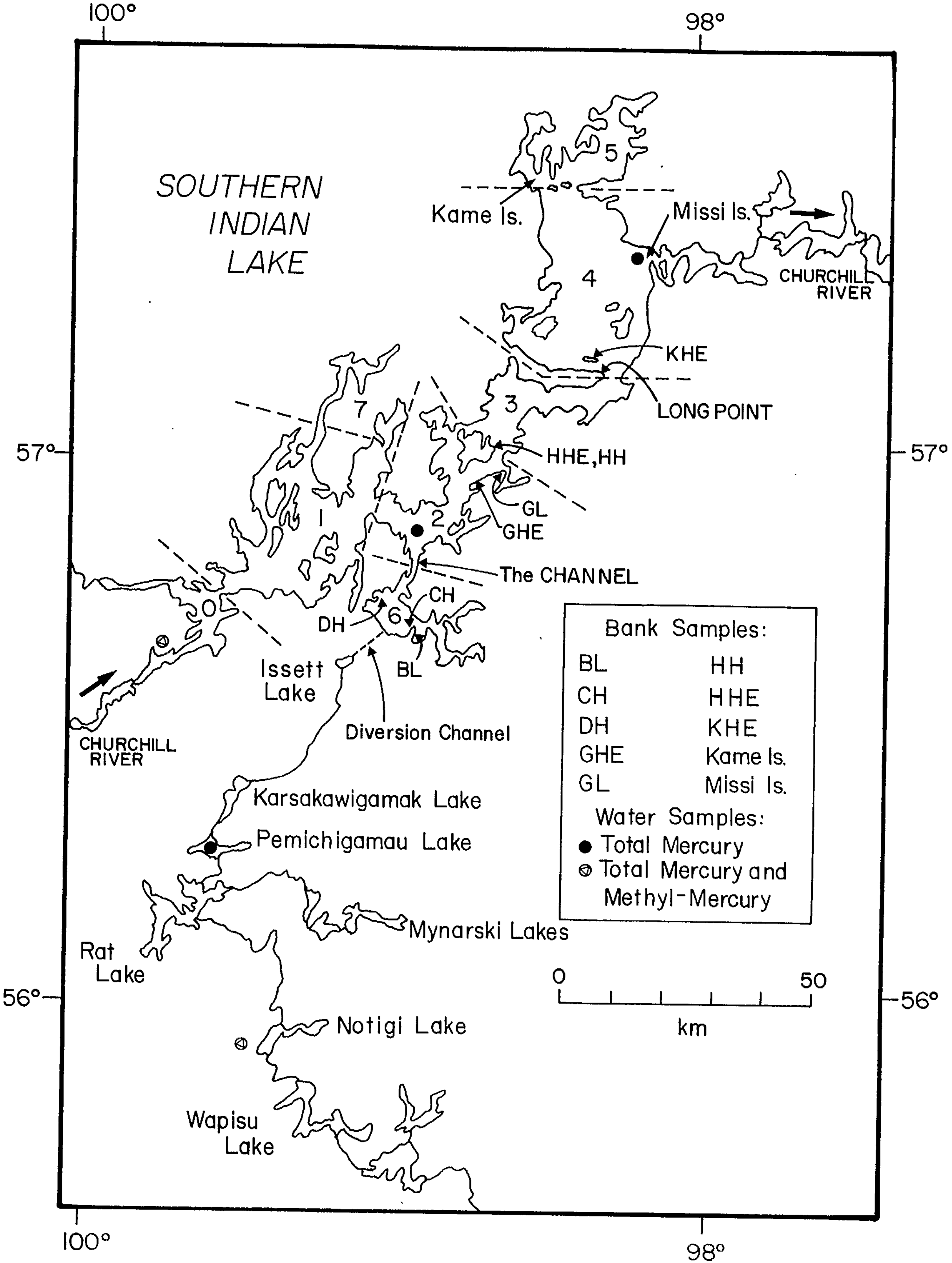

Fig. 1. Map of study area with sampling locations.

Appendix 1: Mercury concentrations in lake whitefish in two areas of Southern Indian Lake and in Issett Lake.

Table A.1. Lake whitefish white muscle mercury concentrations and fork lengths for Area 4, Southern Indian Lake, 1975 and 1978.

1975		1978	
Fork Length (mm)	Mercury Conc. (ppm)	Fork Length (mm)	Mercury Conc. (ppm)
180	.06	355	.38
185	.03	370	.22
195	.04	410	.35
270	.05	390	.35
225	.06	355	.14
220	.07	390	.17
280	.05	225	.16
260	.05	250	.21
370	.04	235	.22
260	.05	205	.16
380	.09	420	.18
370	.05	400	.12
360	.05	405	.33
340	.05	320	.09
385	.06	350	.22
370	.03	325	.19
260	.02		
390	.06		
405	.04		
240	.04		
425	.10		
330	.03		
425	.08		
385	.05		
390	.07		
	$\bar{x}$ = 0.05		$\bar{x}$ = 0.22

Table A.2. Lake whitefish white muscle mercury concentrations and fork lengths for Areas 2 and 6, Southern Indian Lake, 1975 and the Channel, Southern Indian Lake, 1978.

1975		1978	
Fork Length (mm)	Mercury Conc. (ppm)	Fork Length (mm)	Mercury Conc. (ppm)
400	.04	315	.18
250	.04	440	.44
375	.04	445	.24
450	.06	470	.27
260	.06	465	.27
240	.04	440	.35
350	.04	435	.60
300	.06	420	.06
285	.04	390	.38
410	.06	365	.10
315	.05	420	.39
385	.06	425	.22
370	.03	405	.06
245	.04	500	.33
180	.04	420	.43
215	.04	455	.58
360	.05	375	.13
400	.04		
480	.08		
355	.04		
400	.04		
345	.05		
310	.04		
360	.04		
345	.04		
390	.12		
385	.07		
380	.10		
370	.04		
170	.04		
190	.09		
310	.08		
420	.08		
420	.11		
195	.04		
320	.10		
410	.12		
360	.04		
390	.06		
260	.05		
430	.09		
370	.05		
285	.04		
250	.06		
315	.03		
265	.07		
355	.05		
290	.07		
370	.06		
315	.09		
	$\bar{x}$ = 0.06		$\bar{x}$ = 0.30

Table A.3. Lake whitefish white muscle mercury concentrations and fork lengths for Issett Lake, 1975 and 1978.

1975		1978	
Fork Length (mm)	Mercury Conc. (ppm)	Fork Length (mm)	Mercury Conc. (ppm)
310	.14	270	.40
360	.17	335	.29
380	.14	305	.36
300	.17	320	.17
325	.14	315	.40
410	.14		
395	.16		
385	.14		
365	.16		
310	.14		
330	.13		
390	.15		
405	.15		
340	.14		
330	.30		
370	.13		
435	.13		
390	.12		
310	.15		
390	.02		
410	.14		
420	.18		
425	.14		
370	.12		
	$\bar{x}$ = 0.15		$\bar{x}$ = 0.32

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