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INCREASES IN FISH MERCURY LEVELS IN LAKES FLOODED BY THE CHURCHILL RIVER DIVERSION, NORTHERN MANITOBA

by

R.A. Bodaly, R.E. Hecky and R.J.P. Fudge

Department of Fisheries and Oceans

Freshwater Institute

501 University Crescent

Winnipeg, Manitoba R3T 2N6

Running head: Fish mercury increases in flooded lakes

ABSTRACT

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Reservoir creation has often been inferred as a cause of elevated fish mercury concentrations. Increases in fish muscle mercury levels, occurring coincidentally with flooding, are documented for three lakes affected by the Churchill River diversion for which pre- and post-impoundment data were available. For example, pike (Esox lucius) and walleye (Stizostedion vitreum) muscle mercury levels from Southern Indian Lake, which was increased in surface area by 21% by flooding in 1976, increased from baseline values of 0.2 - 0.3 $\mu g\ g^{-1}$ prior to flooding to 0.5 - 1.0 $\mu g\ g^{-1}$ in 1978-1982. Muscle mercury levels from predatory species (pike and walleye) from all ten lakes tested in the Churchill, Rat and Burntwood valleys flooded by the Churchill diversion are near to or exceed the current export marketing limit of 1.0 $\mu g\ g^{-1}$. Because mercury levels in fish from nearby unflooded lakes have not shown recent increases, atmospheric fallout of the metal does not appear to be the cause of the problem. Also, there are no known industrial sources of mercury in the area and no agricultural activity. Post-impoundment mercury levels in predatory fish appeared to be related to the flooded terrestrial area compared to pre-impoundment lake area. They were highest (1.15 - 2.90 $\mu g\ g^{-1}$) in Rat and Notigi lakes which were increased in surface area by 282% were lower (0.60 - 1.53 $\mu g\ g^{-1}$) in lakes immediately below Notigi Reservoir increased in surface area by 31-37%, and were lowest (0.45 - 1.03 $\mu g\ g^{-1}$) in Southern Indian and Wuskwatim Lakes, increased in surface area by 13-21%.

Fish mercury levels responded quickly to impoundment, increasing noticeably within 2 - 3 yrs. Declines in mercury concentrations had not, in general, taken place within 5 - 8 yrs of impoundment, with the exception of whitefish (*Coregonus clupeaformis*) from Southern Indian Lake.

It is hypothesized that observed fish mercury level increases were due to the bacterial methylation of naturally occurring mercury found in flooded soils.

Key words: lake whitefish; walleye; northern pike; mercury, impoundment, river diversion; mercury methylation.

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INTRODUCTION

Fish mercury levels in excess of 0.5 $\mu g\ g^{-1}$ have generally been accepted as evidence of industrial pollution, however fish with high mercury levels occur in many pristine lakes unaffected by industrial sources of mercury (e.g. Koirtyohann et al. 1974; Wobeser et al. 1970; Johnels et al. 1967). This natural variability in fish mercury concentrations from unpolluted environments makes it difficult to interpret high mercury levels in fish from infrequently sampled lakes. Although several studies have implicated reservoir formation as the cause of high fish mercury concentrations observed after flooding (Potter et al. 1975; Abernathy and Cumbie 1977; Cox et al. 1979; Bruce and Spencer 1979) we do not know of any published studies which present both pre- and post-impoundment data on fish mercury concentrations to verify that increases have actually occurred. We present such information here and suggest possible mechanisms based on our knowledge of the environmental changes which accompanied impoundment.

MATERIALS AND METHODS

STUDY AREA

The majority of the flow of the Churchill River in northern Manitoba (Fig. 1), was diverted into the Nelson River basin for hydroelectric purposes by a series of lake and river manipulations over the period 1974-1978. The point of diversion was Southern Indian Lake, flooded 3 m above the mean lake level in 1976. Water was diverted out of Southern Indian Lake via a diversion channel, down the Rat River valley, through a control structure at Notigi Lake, into the Burntwood River and then to the lower Nelson River (Fig. 1). The Notigi control structure flooded lakes in the Rat River valley, including Issett, Pemichigamau, Rat and Notigi lakes, from 8 - 15 m, over the period

1974-76. Lakes downstream of Notigi Lake on, or connected to the Burntwood River, such as Wapisu, Footprint and Wuskwatim, have experienced a rise in water levels of 3-5 m due to increased Burntwood River flows. Table 1 gives the changes in water levels and surface areas of lakes affected by the diversion. Bodaly et al. (in press) give a more detailed description of the Churchill River diversion project.

COLLECTION OF DATA

Sampling of fish for muscle mercury determination was carried out in two different ways: survey sampling and commercial sampling (Bodaly and Hecky 1979). Survey samples were captured by graded mesh experimental gill nets, and, in the case of Southern Indian Lake, samples were separated according to the region of the lake fished. For individual fish, fork length was measured (to the nearest 5 mm) and mercury concentration was determined from a portion of muscle taken from the caudal peduncle area. In the case of commercial samples, fish were removed from time to time from commercial catches and were classified only as to lake of origin. A sample of at least five fish weighing no less than 6.8 kg was taken for each determination. Fillets, one from each fish, were combined and homogenized prior to mercury determinations (in triplicate). Mercury concentrations were determined according to Hendzel and Jamieson (1976) who reported an analytical precision of ±0.025 $\mu g\ g^{-1}$ at 0.5 $\mu g\ g^{-1}$ ~~Hg~~ mercury in fish muscle tissue. Survey samples from Southern Indian Lake and Issett Lake were collected by the authors. Other data is from McGregor (1980) and ~~Fishing and Industry Services~~ Southern Operations Directorate, Department of Fisheries and Oceans, Winnipeg, Manitoba (unpublished data).

Water samples were taken from various locations on Southern Indian Lake, the Churchill River, Pemichigamau Lake and Notigi Lake in September 1978 and

July 1981 (Fig. 1). Samples for total mercury 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 L surface water samples for methylmercury determination were collected in polyethylene carboys. The methylmercury was extracted from acidified water into benzene. Subsequent analysis followed the method of Uthe et al. (1972). The methodological detection limit of the total mercury analysis in water is 5×10^{-6} μg g^{-1} and of the methylmercury analysis is 0.2×10^{-6} μg g^{-1}.

Samples of unflooded bank materials were collected from various locations adjacent to the Churchill River diversion (Fig. 1) in 1981. Subsamples were dried to constant weight at 105°C, ground with a mortar and pestle, and passed through a 1.0 mm mesh screen. A weighed portion was digested with aqua regia, brought to a boil, simmered for one minute, cooled and made to 50 mL volume. The analysis for mercury was completed with the semi-automated procedure of Armstrong and Uthe (1971). Surface sediment samples were collected in the summer of 1980 with an Ekman dredge and treated similarly to the bank material. Suspended sediment was collected by continuous flow centrifugation in August 1980 from known volumes of lake water and subjected to the same treatment except that screening was not necessary. A Sorvall RC2-B centrifuge was used at 14,500 RCF with a flow rate of approximately 50 mL min^{-1}.

RESULTS

Increases in fish mercury levels coincident with flooding

Both pre- and post-impoundment fish mercury data are available for Southern Indian Lake on the Churchill River at the point of diversion, for Issett Lake at the upper end of the Notigi reservoir, and for Wuskwatim Lake, on the Burntwood River below Notigi reservoir. These data demonstrate that mercury levels in fish increased significantly soon after flooding in all three lakes.

Muscle mercury levels in lake whitefish (Coregonus clupeaformis), northern pike (Esox lucius) and walleye (Stizostedion vitreum) from Southern Indian lake have increased substantially from before the impoundment of the lake to after lake impoundment (Table 2). For example, mean mercury concentrations in lake whitefish survey samples from Region 4 were higher after impoundment, with means of 0.22, 0.10, 0.14, 0.08 and 0.11 $\mu g\ g^{-1}$ in 1978 to 1982 respectively, as compared to a pre-impoundment mean of 0.05 $\mu g\ g^{-1}$ in 1975 (Table 2). Similar increases have occurred in lake whitefish from The Channel, Camp 9, and Region 6 (Table 2). Although levels from 1975 were determined from samples stored frozen for approximately three years before analysis, there has apparently been little effect due to storage because 1975 levels reported here are comparable to the lake whitefish mean mercury concentration of 0.05 $\mu g\ g^{-1}$ determined prior to flooding (1969-1973) from 6 samples removed from commercial shipments (Table 2). Unfortunately, mercury levels in commercial shipments have not been monitored since 1973. Hendzel (personal communication) reports no detectable changes in mercury concentrations in fish tissue stored frozen for many months. Frozen storage, if accompanied by severe dehydration, might increase mercury concentrations on a wet weight basis, and therefore the mercury concentrations observed for the 1975 whitefish samples represent maximum estimates.

Samples of the two predatory fish species landed by the Southern Indian Lake commercial fishery, walleye and northern pike, also show post-impoundment increases in muscle mercury levels as compared to pre-impoundment levels (Table 2). Mercury levels in walleye commercial samples were relatively stable at 0.2-0.3 μg g^{-1} over the period 1971 to 1977 but were much higher (0.57-0.75 μg g^{-1}) in 1978-1982. Northern pike mercury levels were somewhat higher than walleye before lake impoundment, in the range 0.25-0.35 μg g^{-1} over the period 1971-1973. Levels in pike may have been elevated in 1976-1978 to 0.4-0.5 μg g^{-1} and means in 1979-1982 (0.67-0.95 μg g^{-1}) were much above pre-impoundment levels.

Mean mercury levels in walleye from Wuskwatim Lake were relatively stable over the pre-impoundment period 1970-1977 at 0.25-0.44 μg g^{-1} but increased to 0.76, 1.00, and 0.89 μg g^{-1} in 1979, 1980 and 1981 respectively (Table 3). Whitefish mercury concentrations also increased, rising from 0.08 μg g^{-1} in 1970 to 0.33 ppm in 1981 (Table 3). Mercury concentrations in lake whitefish muscle from Issett Lake doubled from a mean of 0.15 μg g^{-1} in 1975, prior to Churchill River diversion, to a mean of 0.32 μg g^{-1} in 1978, after Churchill River diversion (Table 3).

It is well known that mercury concentrations in fish tend to increase with fish size (Scott and Armstrong 1972; Scott 1974; Huckabee et al. 1979), however, increases in mercury levels in fish in new impoundments noted here were not due to changes in the average size of fish sampled. Significant changes in the average size of survey samples have, in general, not occurred and where changes in fish size occurred, average mercury levels did not usually follow average fish sizes (Tables 2 and 3). In the case of commercial samples, mean fish size tends to be held rather constant by the use of one size of commercial gillnet mesh. Furthermore, significant correlations between fish size and mercury concentrations were not the rule for pre- or post-impoundment survey samples from the Churchill River diversion area, significant correlations were observed in a majority of survey samples only for pike (14 of 22 samples) whereas significant correlations were observed in a minority of samples of whitefish (7 of 20 samples) and walleye (9 of 24 samples).

Regional differences in post-impoundment mercury levels

Only post-impoundment data were available for other flooded lakes located on the route of the diverted Churchill River. All of these lakes contained fish with mercury levels much higher than expected background concentrations (Table 3). In general, mercury levels in predatory fish after impoundment were highest in lakes now covered by the Notigi reservoir, were moderately high in lakes flooded by diversion flow downstream of Notigi control structure, and were lowest in Southern Indian Lake (Tables 2 and 3). Mercury levels in predatory fish from Notigi reservoir lakes ranged from ≈0.6-2.9 μg g^{-1}, while the comparable range for lakes below Notigi was ≈0.6-1.5 μg g^{-1} and for Southern Indian Lake was ≈0.4-1.0 μg g^{-1}. Mercury levels in whitefish tended to be higher in lakes below Notigi reservoir and lowest in Southern Indian Lake.

Time course of elevated fish mercury levels

Mercury levels in predatory fish became elevated within 2-3 years of lake impoundment and there was no indication of general declines from peak levels within 5-8 years of impoundment. Predatory species from Southern Indian Lake showed elevated mercury levels by 1978, two years after flooding. There were no trends towards declining levels over the period 1978-1982 (Table 2). Mercury concentrations in walleye were relatively stable both in survey and commercial samples over this period. Survey samples of pike taken from specific regions of the lake show generally increasing mercury levels over 1978-82, and mercury levels in commercial shipments were highest in 1981

(Table 2). In lakes now covered by the Notigi reservoir, impounded over the period 1974-1976, high fish mercury levels were evident by 1977-1978 when the lakes were first sampled (Table 3). Mercury levels in predatory fish showed little trend over the period 1977-1982, but sampling was irregular (Table 3). In lakes downstream of the Notigi control structure, flooded by diversion flow in 1976-1978, elevated fish mercury levels were evident by 1977-1979 (Table 3). As with Notigi reservoir lakes, sampling was irregular and post-impoundment trends are not obvious.

Mercury levels in whitefish from Southern Indian Lake also responded quickly to flooding and were elevated by 1978, two years after lake impoundment, when first sampled (Table 2). However, in contrast to mercury levels in predatory fish from all impounded lakes in the area, whitefish mercury levels from Southern Indian Lake decreased consistently over the period 1978-1982, although pre-impoundment levels had not been reached by 1982.

Water, Soil, and Sediment Mercury Concentrations

Total mercury concentrations in water collected from 17 locations (Fig. 1) in 1978 and 1981 were $<5 \times 10^{-6}$ $\mu g\ g^{-1}$, the limit of detection with the methods and sample volumes used. Similarly, 13 of the 14 analyses for methylmercury in water were below the limit of detection, 0.2×10^{-6} $\mu g\ g^{-1}$, while a concentration of 0.4×10^{-6} $\mu g\ g^{-1}$ was observed in the forebay of the Notigi Reservoir.

Terrestrial soils are a possible source of mercury in new impoundments. Soils underly approximately three-quarters of the surface area of Notigi Reservoir (Table 1) and eroding banks are a continuing source of terrestrial material to the Southern Indian lake reservoir (Hecky et al., this volume p. 00). Bank materials generally consist of three recognizable horizons: an upper layer of moss, litter and humus, a second layer of highly organic surface soils (soil horizon A) and the inorganic subsoil (soil horizon C). The greatest mass of material brought into suspension due to shore erosion is of fine grained silts and clays which originate from extensive glacio-lacustrine deposits surrounding the lake (Newbury and McCullough this volume, p. 00). Mercury concentrations in the upper, organic rich soil horizons are clearly higher than in the inorganic C horizon (Table 4). Lake sediment mercury concentrations are similar to the eroding, inorganic bank material but lower than the organic horizons (Table 4). Suspended sediments collected from lake water are substantially higher in mercury concentration than surface sediments collected from the lake bottom (Table 4).

DISCUSSION

The present data show that increases in fish mercury concentrations have occurred coincidentally with increases in water level and that high mercury levels have been observed after inundation in all lakes flooded by the Churchill River diversion. Pre-flooding data available for Southern Indian Lake, Issett Lake and Wuskwatim Lake show increased fish mercury concentrations soon after increases in water levels. Lakes on the diversion route between Issett and Wuskwatim, for which there were no pre-diversion data (Rat, Notigi, Wapisu and Footprint lakes) show high fish mercury concentrations in years immediately following diversion and flooding, and these concentrations presumably represent increases over pre-flooding concentrations. Increases in fish mercury concentrations appear to be restricted to lakes flooded for the Churchill River diversion and there is no suggestion that similar increases have occurred in undisturbed lakes over the same time period throughout northern Manitoba. In fact, there are over 30 lakes in northern Manitoba (north of the 55th parallel) for which fish mercury levels have been determined from commercial shipments during the 1970's which show no trends of increasing fish mercury levels (data from ~~Fishing and Industry Services~~ Southern Operations Directorate, Department of Fisheries and Oceans, Winnipeg, Manitoba). This indicates that the recent increases in fish mercury levels in Southern Indian Lake and lakes on the Rat and Burntwood Rivers are probably not directly due to atmospheric fallout. Mercury analyses on a 20 cm sediment core from Southern Indian Lake show a slow, constant increase in Hg concentration from the base of the core to the top, resulting in a 2X top to bottom differential in mercury concentration (G.J. Brunskill, unpubl. data), but there is no evidence of dramatic increase in ~~Hg~~ mercury deposition prior to flooding. An approximate doubling in mercury flux to the sediments since 1900 has been identified at a number of "pristine" locations and has been attributed to an increase in atmospheric fallout of mercury because of industrialization (Kemp et al. 1978; Weiss et al. 1975). The observed increase in the Southern Indian Lake core is consistent with this apparent global trend. Modern deposition rates of mercury in Southern Indian Lake (G.J. Brunskill, pers. comm.) are below the pre-modern deposition rates for the upper Great Lakes (Kemp et al. 1978) and are similar to the deposition rates on the Greenland glacier (Weiss et al. 1975). Suspended sediments collected in Southern Indian Lake after impoundment (Table 4) are enriched in mercury relative to older deposited sediments; this may reflect a recent change in mercury availability in the lake.

There are no known point sources of mercury and no agricultural activity in the Churchill diversion area which could supply a sudden surge in mercury deposition beginning in 1976. Although it is not possible to rule out the possibility that all the geographic areas listed above might have unusual geological formations which provide a rich local source of mercury, it seems unlikely that mercury-rich mineral formations are the ultimate cause of the elevated fish mercury concentrations in all these reservoirs. Source materials at Southern Indian Lake tend to be low or average in their mercury content when compared to similar materials analyzed elsewhere (Andren and Nriagu 1979; Andersson 1979). The modern mercury deposition rate in Southern Indian lake prior to flooding in 1976 is among the lowest reported in the literature (G.J. Brunskill, pers. comm.). We conclude that there is no reason to believe that the Southern Indian Lake-Notigi region has unusually high mercury concentrations in source material. Instead it seems that reservoir formation and associated inundation of land in itself has led to higher fish mercury concentration.

The hypothesis that reservoir formation can lead to elevated fish mercury levels was initially made by Potter et al. (1975) and Abernathy and Cumbie (1977). A similar hypothesis has more recently been made by others (Bruce and Spencer 1979; Waite et al. 1980; Meister et al. 1979; Cox et al. 1979). These hypotheses have emphasized that reservoirs provide new sources of mercury in inundated soils (Abernathy and Cumbie 1977; Meister et al. 1979) or increased availability of naturally transported mercury because of increased retention of inflowing material (Potter et al. 1975). Problems associated with elevated fish mercury levels in newly impounded reservoirs are quite widespread in North America. They have been reported in Labrador, Saskatchewan, Manitoba, Arizona, Illinois, South Carolina, (references above), Utah (Smith et al. 1974), Idaho (Benson et al. 1976; Kent and Johnson 1979), Mississippi (Knight and Herring 1972), and elsewhere. It now seems clear that this is a widespread phenomenon which has come to the attention of fisheries workers in the last decade due to the recent introduction of routine testing of fish for mercury levels.

Mercury in fish muscle exists predominantly in the organic or methylmercury form (Westoo 1966). The methylation of inorganic mercury is known to be primarily bacterially mediated in nature (Beijer and Jernelov 1979; Bisogni 1979). Increased bacterial production due to degradation of flooded terrestrial vegetation, peat and humus probably serves to promote mercury methylation; Furutani and Rudd (1980) showed that an increase in microbial substrate resulted in increased rates of mercury methylation. We hypothesize that, in lakes flooded by the Churchill River diversion, elevated fish mercury levels were due to the bacterial methylation, of naturally occurring mercury found in flooded soils. The apparent relationship over the Churchill River diversion system between the increase in lake surface area and mercury levels in predatory fish, where fish mercury levels were highest in the extensively flooded Notigi reservoir, supports this hypothesis. The primary source of mercury was probably the upper, organic soil horizon because mercury levels in this soil layer were much higher than in inorganic subsoil layers. Inorganic subsoil is apparently not acting as a major source of mercury because the addition of large amounts of inorganic subsoil to the water column through shore erosion in Southern Indian Lake (Newbury et al. 1978) did not result in fish mercury levels approaching those found in the Notigi reservoir where shoreline erosion was negligible but increase in area flooded was greater.

Water mercury levels throughout the Churchill River diversion system were very low. This has been reported for other new reservoirs where fish mercury levels were elevated (Cox et al. 1979; Potter et al. 1975; Abernathy and Cumbie 1977) and was expected because the geochemistry of inorganic mercury strongly favors association with particulate phases (Cranston and Buckley 1972; Hannan and Thompson 1977), and the biogeochemistry of methylmercury strongly favors association with biota owing to its aqueous and lipid solubility and affinity for sulfhydryl groups (Carty and Malone 1979). In Southern Indian Lake, water concentrations were <5 x 10^{-6} μg g^{-1} (or 5 pg g-1) while mercury concentrations on suspended sediments were 0.20 μg g^{-1}, a concentration factor of at least 2 x 10^5, and mercury concentrations in pike were approximately 0.60 μg g^{-1}, a minimum concentration factor of 6 x 10^5. These concentration factors are similar to those reported in the literature (Potter et al. 1975).

Average muscle mercury levels in predatory species (walleye and pike) exceed the Canadian marketing standard of 0.5 μg g^{-1} (and usually the U.S. standard of 1.0 μg g^{-1}) in every lake on the Churchill, Rat and Burntwood rivers flooded by the Churchill River diversion project. The widespread nature of the high fish mercury level - new reservoir association makes it imperative that elevated fish mercury levels be considered in all impact assessments of proposed reservoirs.

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Table 1. Changes in water level and surface area of several lakes affected by the Churchill River diversion project. Areas and levels are estimated under long term mean levels prior to diversion and under projected mean levels after full Churchill River diversion. Sources: McCullough (1981); Brown (1974); Vitkin (1979); D. W 'dsor, Manitoba Hydro, pers. comm.

Lake	Pre-impoundment level (m)	Post-impoundment level (m)	Pre-impoundment area (km^2)	Post-impoundment area (km^2)	Relative change %
Southern Indian	255.0	258.0	1977	2391	+21
Notigi Reservoir[1]			153	584	+282
Issett	250.6	258.2	3.7		
Karsakuwigamak	248.1	258	18.8		
Pemichigamau	247.8	258	19.3		
Central Mynarski	251.1	258	11.5		
West Mynarski	249.0	258	6.2		
Rat	247.8	257.9	78.4		
Notigi	242.0	257.2	15.1		
Wapisu	239.9	243.2	49	67	+37
Threepoint & Footprint	239.0	242.6	75	103	+31
Wuskwatim	231.0	233.0	70	79	+13

[1] Pre-impoundment water area for Notigi is the sum of the several lakes (listed under Notigi Reservoir) which existed before impoundment.

Table 2. Fish mercury levels ($\mu g\ g^{-1}$) from lake whitefish, walleye and northern pike from Southern Indian Lake. Region of lake given for survey samples (see methods for difference between survey and commercial sample). See Fig. 1 for location of region of lake.

Species	Region	Year	Mean mercury concentration ($\mu g\ g^{-1}$)	Range of mercury concentration	# samples	Mean fork length(cm) of survey sample
Whitefish	The Channel	1975[1]	0.06	0.03-0.12	50	33.2
		1978	0.30	0.06-0.60	17	42.3
		1979	0.25	0.04-0.55	26	33.9
		1980	0.21	0.02-0.42	24	33.5
		1981	0.20	0.04-0.34	25	34.2
		1982	0.09	0.03-0.27	25	40.1
	Camp 9	1975[2]	0.05	0.03-0.08	25	33.5
		1979	0.13	0.06-0.26	40	40.1
		1980	0.13	0.04-0.59	28	37.9
		1981	0.10	0.04-0.35	24	35.1
		1982	0.09	0.03-0.27	25	40.1
	Region 4	1975	0.05	0.02-0.10	25	31.6
		1978	0.22	0.09-0.38	16	33.7
		1979	0.10	0.06-0.30	68	37.0
		1980	0.14	0.05-0.37	27	37.0
		1981	0.08	0.03-0.32	67	35.3
		1982	0.11	0.06-0.21	25	39.0
	Region 6	1975	0.07	0.03-0.12	25	32.9
		1979	0.31	0.05-0.55	30	38.6
		1980	0.20	0.04-0.44	20	33.3
		1981	0.14	0.03-0.38	26	32.6
		1982	0.11	0.01-0.36	36	32.6
	(Commercial)	1969	0.05	-	1	-
		1970	0.05	0.02-0.08	2	-
		1972	0.11	-	1	-
		1973	0.02	0.02-0.02	2	-
Walleye	The Channel	1979	0.47	0.25-2.19	30	33.3
		1980	0.56	0.29-2.04	33	39.3
		1981	0.55	0.36-1.22	32	38.7
		1982	0.45	0.23-1.41	24	38.9
	Camp 9	1979	0.59	0.32-1.80	11	40.6
		1980	0.53	0.37-0.76	14	38.8
		1981	0.45	0.36-0.51	5	36.2
		1982	0.47	0.32-0.65	25	40.6
	Region 6	1978	0.80	0.46-1.20	15	43.5
		1979	0.47	0.06-1.14	21	36.5
		1980	0.59	0.33-1.03		37.6
		1981	0.64	0.32-1.94	26	38.2
		1982	0.78	0.31-1.56	25	35.5
	(Commercial)	1971	0.19	0.16-0.22	6	-
		1972	0.21	0.18-0.23	3	-
		1973	0.28	0.20-0.35	3	-
		1975	0.30	0.22-0.38	2	-
		1976	0.24	0.20-0.32	4	-
		1977	0.26	0.23-0.30	2	-
		1978	0.57	0.33-1.12	7	-
		1979	0.75	0.47-1.21	6	-
		1980	0.54	0.35-0.92	3	-
		1981	0.62	0.26-1.26	20	-
		1982	0.62	0.57-0.67	5	-
Pike	The Channel	1979	0.57	0.29-0.89	35	49.7
		1980	0.57	0.05-1.11	38	53.2
		1981	0.64	0.42-1.00	25	52.0
		1982	0.77	0.48-1.09	25	54.2
	Camp 9	1979	0.58	0.36-1.10	35	55.4
		1980	0.61	0.41-1.01	31	56.6
		1981	0.66	0.43-0.96	24	54.4
		1982	0.66	0.43-0.96	25	60.3
	Region 4	1979	0.49	0.30-1.20	54	52.8
		1980	0.63	0.45-0.91	28	53.9
		1981	0.72	0.19-1.13	25	55.2
		1982	0.63	0.35-0.82	24	58.2
	Region 6	1978	0.77	0.28-1.72	15	66.6
		1979	0.69	0.42-1.21	60	53.0
		1980	0.78	0.42-2.55	34	53.7
		1981	0.89	0.65-1.15	25	55.4
		1982	0.96	0.38-1.54	28	55.2
	(Commercial)	1971	0.26	0.24-0.29	4	-
		1972	0.32	0.24-0.40	5	-
		1973	0.30	0.26-0.33	3	-
		1976	0.47	0.26-1.02	10	-
		1977	0.43	0.42-0.45	2	-
		1978	0.50	0.25-0.83	7	-
		1979	0.88	0.53-1.51	9	-
		1980	0.67	0.45-1.12	14	-
		1981	0.95	0.53-2.04	28	-
		1982	0.90	0.25-1.39	17	-

[1] This sample is a combined sample from Regions 2 and 6 (see Fig. 1).

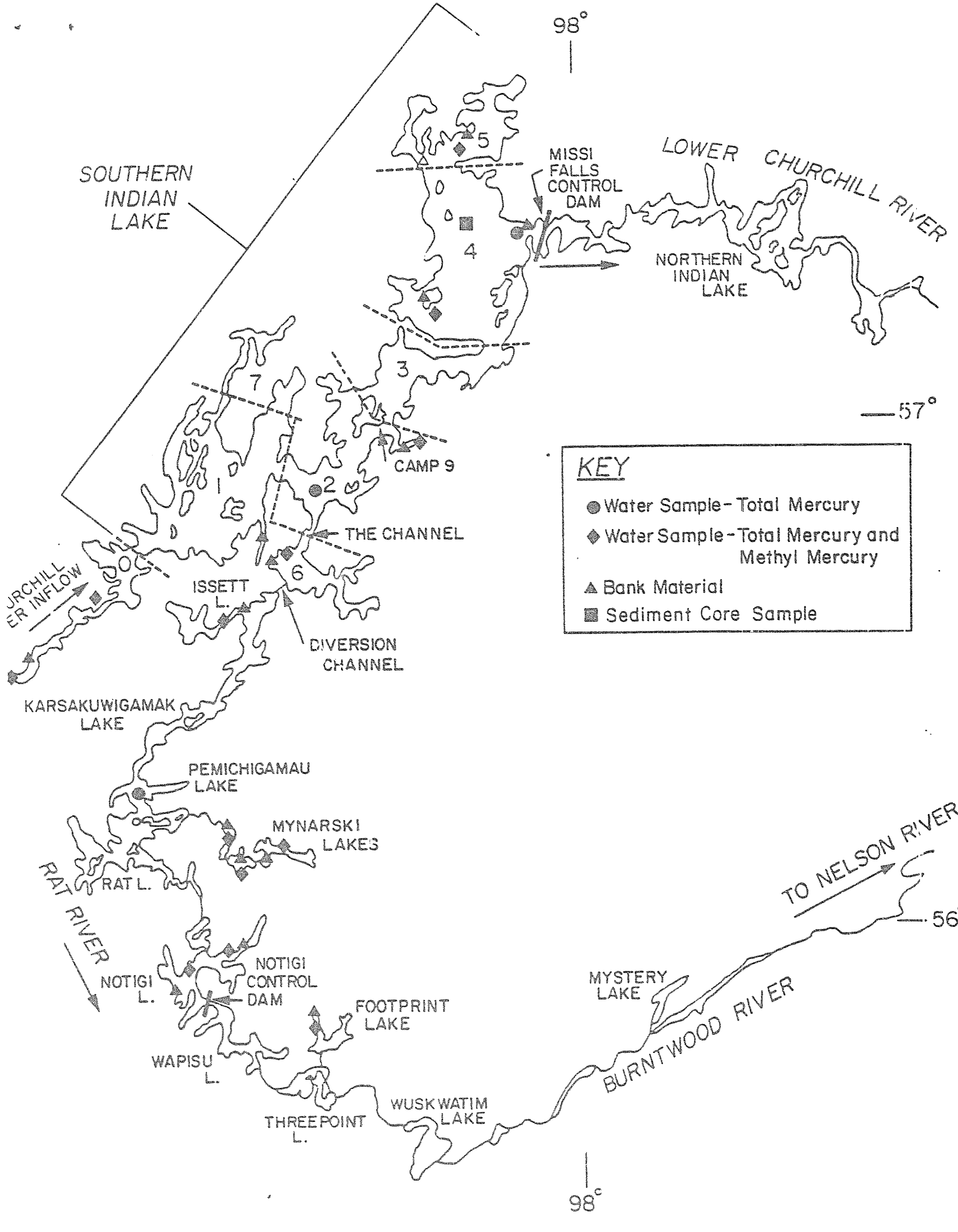
[2] This sample was taken from Region 2 (see Fig. 1).

Table 3. Fish mercury levels (µg g^{-1}) from lake whitefish, walleye and northern pike taken from Rat and Burntwood River basin lakes flooded by the Churchill River diversion. See Fig. 1 for location of lakes. Issett, Rat and Notigi lakes are part of Notigi reservoir; other lakes are downstream of Notigi Reservoir. Type of sample and number of samples (see Methods) is also indicated.

Lake	Species	Year	Mean mercury concentration (µg g^{-1})	Range of mercury concentration	Type of sample	# samples	Mean fork length (cm) of survey sample
Issett	Whitefish	1975	0.15	0.02-0.30	survey	24	36.3
		1978	0.32	0.17-0.40	survey	5	31.0
		1982	0.21	0.12-0.36	survey	25	38.4
	Walleye	1978	1.52	1.24-1.95	survey	5	38.9
		1982	0.79	0.20-2.52	survey	19	34.7
	Pike	1978	0.61	0.37-0.74	survey	5	57.3
		1982	0.90	0.36-1.75	survey	26	59.6
Rat	Whitefish	1978	0.40	0.26-0.59	survey	5	43.9
		1978	0.37	-	commercial	1	-
		1980	0.32	0.15-0.61	survey	24	42.2
		1980	0.34	-	commercial	1	-
	Walleye	1978	2.54	2.39-2.67	commercial	5	-
		1978	2.56	2.17-3.61	survey	26	44.9
		1979	2.32	1.68-3.29	survey	25	45.0
		1980	1.15	0.41-3.37	survey	22	40.8
		1980	1.15	-	commercial	1	-
	Pike	1978	2.14	2.04-2.25	commercial	5	-
		1978	2.05	1.47-2.49	survey	24	69.8
		1980	2.32	-	commercial	1	-
Notigi	Whitefish	1980	0.12	0.07-0.25	survey	6	42.1
		1981	0.23	0.12-0.71	survey	38	30.9
	Walleye	1978	1.41	0.19-2.91	survey	19	42.2
		1978	1.32	0.26-2.32	commercial	3	-
		1980	2.90	2.11-3.47	survey	4	45.2
		1980	2.59	-	commercial	1	-
		1981	1.88	0.95-2.55	survey	29	41.6
		1982	1.23	0.98-1.63	survey	6	50.3
		1982	1.11	-	commercial	1	-
	Pike	1977	1.59	-	commercial	1	-
		1980	1.95	1.62-2.29	survey	5	78.8
		1981	1.70	0.24-2.82	survey	50	58.1
		1982	1.85	1.32-2.38	survey	10	73.8
		1982	2.06	1.91-2.21	commercial	2	-
Wapisu	Walleye	1977	1.17	0.14-3.03	survey	91	41.1
		1977	1.33	0.80-1.81	commercial	3	-
	Pike	1977	1.08	0.32-2.25	survey	38	67.2
		1977	1.53	1.48-1.61	commercial	3	-
Footprint	Walleye	1978	0.82	0.29-2.61	survey	40	38.2
		1980	0.92	0.31-1.72	survey	12	39.4
		1981	1.10	0.71-1.76	survey	30	37.6
	Pike	1978	0.60	0.28-0.90	survey	36	45.7
		1980	1.38	0.82-3.37	survey	8	52.6
		1981	1.12	0.83-1.74	survey	14	52.0
Threepoint	Whitefish	1980	0.56	0.34-0.91	survey	10	42.9
		1981	0.23	0.11-0.41	survey	16	33.3
	Walleye	1980	1.18	0.62-1.31	survey	10	40.3
		1981	1.35	0.84-2.05	survey	42	38.1
	Pike	1980	1.28	0.49-3.05	survey	10	68.8
		1981	1.33	0.44-2.27	survey	28	51.7
Wuskwatim	Whitefish	1970	0.08	-	commercial	1	-
		1981	0.33	0.18-0.78	survey	28	39.8
	Walleye	1970	0.34	-	commercial	1	-
		1971	0.25	-	commercial	1	-
		1973	0.40	-	commercial	1	-
		1974	0.44	-	commercial	1	-
		1975	0.35	-	commercial	1	-
		1976	0.26	-	commercial	1	-
		1977	0.38	-	commercial	1	-
		1979	0.76	0.25-2.18	survey	90	41.5
		1980	1.00	0.78-1.41	survey	19	41.3
		1981	0.89	0.62-1.36	survey	34	39.9
	Pike	1979	0.91	0.21-5.31	survey	75	56.0
		1980	1.03	0.79-1.21	survey	7	60.5
		1981	0.80	0.47-1.98	survey	25	51.4
Mystery	Walleye	1979	1.13	0.53-1.75	survey	33	46.2
	Pike	1979	0.79	0.23-1.64	survey	45	54.1

Table 4. Mean and range of total mercury concentrations in various possible source materials at Southern Indian Lake and Notigi Reservoir.

Source	Date sampled	n	Total mercury content ($\mu g\ g^{-1}$) Mean	Range
Moss/litter/humus	July-Aug 1981	83	0.095	<0.005-0.290
Soil A horizon	July-Aug 1981	47	0.090	<0.005-0.220
Soil C horizon	July-Aug 1981	60	0.041	<0.005-0.180
Lake sediment	July-Aug 1980	28	0.036	0.010-0.070
Suspended sediment	Aug 1980	4	0.255	0.120-0.360
Water	Sept 1978 and July 1981	17	$<5 \times 10^{-6}$	-


98°
SOUTHERN INDIAN LAKE
MISSI FALLS CONTROL DAM
LOWER CHURCHILL RIVER
NORTHERN INDIAN LAKE
5
4
3
7
1
2
6
57°
CAMP 9
THE CHANNEL
KEY
Water Sample - Total Mercury
Water Sample - Total Mercury and Methyl Mercury
Bank Material
Sediment Core Sample
URCHILL ER INFLOW
ISSETT L.
DIVERSION CHANNEL
KARSAKUWIGAMAK LAKE
PEMICHIGAMAU LAKE
MYNARSKI LAKES
RAT L.
RAT RIVER
TO NELSON RIVER
56
NOTIGI L.
NOTIGI CONTROL DAM
MYSTERY LAKE
FOOTPRINT LAKE
BURNTWOOD RIVER
WAPISU L.
WUSKWATIM LAKE
THREEPOINT L.
98°