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Postimpoundment Time Course of Increased Mercury Concentrations in Fish in Hydroelectric Reservoirs of Northern Manitoba, Canada

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Abstract Mercury (Hg) concentrations in fish in boreal reservoirs have been shown to be increased for up to 3 decades after impoundment. However, the time course of increased concentrations is not well known. The purpose of this study was to determine the evolution of Hg concentrations in fish in the boreal reservoirs of northern Manitoba, Canada, and its relationship with severity of flooding. We determined total Hg concentrations in three species of fish for up to 35 years after impoundment in 14 lakes and lake basins. Postimpoundment trends depended on fish species and reservoir. In the benthivorous lake whitefish (*Coregonus clupeaformis*), Hg concentrations increased after flooding to between 0.2 and 0.4 μg g^{-1} wet weight compared with preimpoundment concentrations between 0.06 and 0.14 μg g^{-1} and concentrations in natural lakes between 0.03 and 0.06 μg g^{-1}. Hg concentrations in lake whitefish were usually highest within 6 years after lake impoundment and took 10 to 20 years after impoundment to decrease to background concentrations in most reservoirs. Hg concentrations in predatory northern pike (*Esox lucius*) and walleye (*Sander vitreus*) were highest 2 to 8 years after flooding at 0.7 to 2.6 μg g^{-1} compared with preimpoundment concentrations of 0.19 to 0.47 μg g^{-1} and concentrations in natural lakes of 0.35 to 0.47 μg g^{-1}. Hg concentrations in these predatory species decreased consistently in subsequent years and required 10 to 23 years to return to background levels. Thus, results demonstrate the effect of trophic level on Hg concentrations (biomagnification). Peak Hg concentrations depended on the amount of flooding (relative increase in lake surface area). Asymptotic concentrations of approximately 0.25 μg g^{-1} for lake whitefish and 1.6 μg g^{-1} for both walleye and northern pike were reached at approximately 100% flooding. Downstream effects were apparent because many reservoirs downstream of other impoundments had higher Hg concentrations in fish than would be expected on the basis of flooding amount.

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Increased mercury (Hg) concentrations in fish have been reported in boreal (eg, Bodaly et al. 1984a; Lodenius et al. 1983; Verta et al. 1986; Schetagne & Verdon 1999), temperate (Cox et al. 1979; Abernathy & Cumbie 1977), and tropical regions (Yingcharoen & Bodaly 1993; Roulet & Lucotte 1995). Work on Manitoba reservoirs was the first to demonstrate actual increases in concentrations of Hg in fish as a result of reservoir formation (Derksen 1973; Bodaly & Hecky 1979; Bodaly et al. 1984a). Bodaly and Hecky (1979) and Bodaly et al. (1984a) initially hypothesized that increased Hg concentrations in fish in newly flooded reservoirs was caused by the bacterial methylation of Hg found in flooded soils. This hypothesis has been confirmed by experimental studies in which terrestrial materials were experimentally flooded (Hecky et al. 1991; Therien & Morrison 1999), in studies of experimental

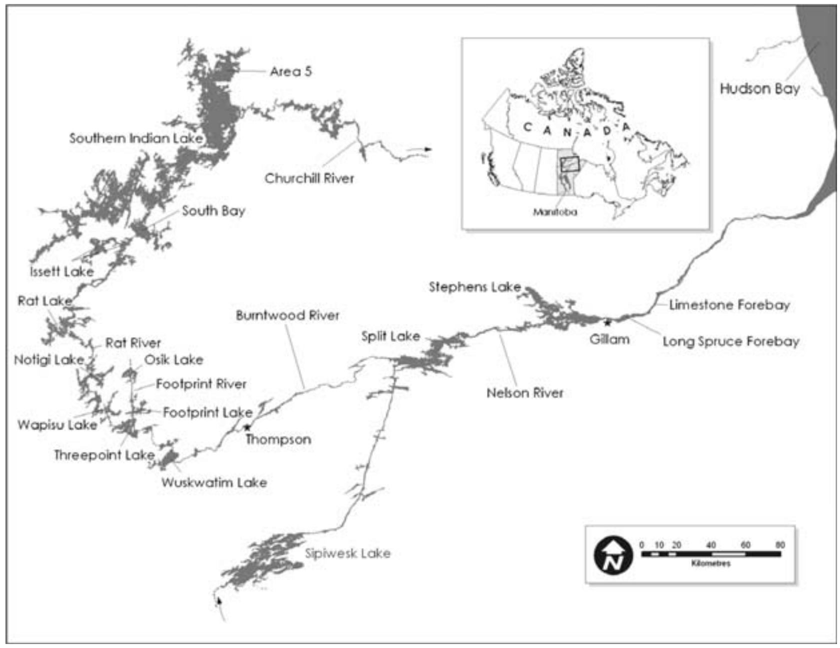

Fig. 1 Northern Manitoba (Canada) study area, including reservoirs sampled

reservoirs (Bodaly & Fudge 1999; Hall et al. 2005; Kelly et al. 1997; St. Louis et al. 2004), and in studies of boreal reservoirs (Hecky et al. 1987; Louchouarn et al. 1993; Lucotte et al. 1999). Bodaly et al. (1997) reviewed published evidence and concluded that new methyl mercury (MeHg) was likely produced by flooding. However, the duration of increased Hg concentrations is not well known because most reservoirs have been monitored for only limited periods of time.

Previous studies on the temporal evolution of Hg concentrations in northern pike (*Esox lucius*) from reservoirs in Finland found that the periods of observation, often lasting >20 years, were not sufficient to document returns to background Hg concentrations (Verta & Porvari 1995). Many reservoirs in northern Quebec have been monitored for Hg concentrations in predatory fish for >15 years, but similar to the Finnish reservoirs, returns to background levels have not yet been observed (Schetagne & Verdon 1999). The purpose of this study was to determine the evolution of Hg concentrations in fish in the boreal reservoirs of northern Manitoba, Canada, and its relationship with severity of flooding using a data set for up to 35 years after impoundment. Temporal trends of Hg concentrations are presented here for three species: lake whitefish (*Coregonus clupeaformis*), walleye (*Sander vitreus*), and northern pike (*E. lucius*) in 14 reservoirs and basins (including one lake receiving water from upstream impoundments). We hypothesized that Hg concentrations in predatory fish would be increased for at least 20 years after impoundment and that Hg concentrations in nonpiscivorous fish would be increased no longer than 20 years after impoundment. We further hypothesized that peak levels and duration of increase would depend on the degree of flooding and the existence of upstream flooding.

Methods

Study Area

The reservoirs sampled are located in northern Manitoba, Canada (approximately 56°N to 57°N latitude and 95°W to 100°W longitude) within the Precambrian Shield and boreal forest zone (Fig. 1). The area consists mostly of bedrock overlain with glaciofluvial and glaciolacustrine sediments. It is north of the southern limit of permafrost, in the zones of ''scattered'' and ''widespread'' permafrost. Lakes and wetlands cover approximately one third of the land surface. Summers are short and cool (mean July temperature is 15°C to 16°C), and winters are long and cold (mean January temperature is –25°C to –27°C). Lakes are ice-covered for approximately 7 months of the year. Spruce, jack pine, and tamarack are the dominant tree species. Sphagnum moss is common on the forest floor and in wetlands. Newbury et al. (1984) and Bodaly et al. (1984b) have already described the area of the Churchill River Diversion (the northern portion of the study area) in great detail.

Hydroelectric development in northern Manitoba took place mainly in the 1970s (Fig. 1 and Table 1). Approximately 75% of the flow of the Churchill River was diverted into the Nelson River basin by a series of lake and channel manipulations during the period from 1973 to 1977. In 1973, a control dam located at the outlet of Notigi Lake was closed, and lakes in the Rat River valley between the

Table 1 Reservoirs included in the analysis of fish mercury concentrations

Reservoir	River/Reach	Year of flooding	Flood (%)	Commercial data		Survey data	
				No. of years	Time span	No. of years	Time span
Southern Indian	Churchill	1976	20.9	8	1970–1978	15	1975–1998
Issett	Rat	1975	465.4	–	–	13	1975–1998
Rat	Rat	1974	159.8	–	–	15	1975–1999
Notigi	Rat	1974	248.6	3	1977–1982	11	1978–2002
Wapisu	Rat	1977	32.2	–	–	5	1977–2001
Threepoint	Burntwood, lower	1977	47.7	–	–	14	1980–1998
Footprint	Footprint	1977	39.3	–	–	8	1978–2001
Wuskwatim	Burntwood, lower	1977	48.1	7	1970–1977	11	1979–2002
Osik	Footprint	1977	15.6	–	–	8	1982–2001
Split	Nelson, lower	1977	<0.1	1	1970	22	1972–2002
Stephens	Nelson, lower	1970	236.6	1	1981	12	1983–2002
Long Spruce	Nelson, lower	1977	87.5	–	–	7	1985–1996
Sipiwesk	Nelson, upper	1961	20.6	–	–	22	1972–1996

[a] River system, year of flooding, percentage flooding, and the number and range (between 1970 and 2002) of years with data used from commercial and survey sources are indicated. Sometimes the data set reflects combined data years from the three different fish species (lake whitefish, northern pike, and walleye) when the full record was not available for each species. Overlap of commercial and survey data indicates that early survey data were not available for all species and commercial data were used. Percentage of flooding was calculated as flooded area × 100/preflood area

Notigi and Issett lakes, including Rat and Issett lakes, were flooded by the creation of the Notigi reservoir during the period from 1973 to 1976 (Fig. 1 and Table 1). In the summer of 1976, the level of Southern Indian Lake (SIL) was increased by 3 m with the closure of the Missi Falls control dam. This began the flow of Churchill River water through an artificial diversion channel linking the South Bay basin of SIL with the headwaters of the Notigi reservoir. These increased flows of the Notigi reservoir resulted in flooding of the lakes, including Threepoint and Wuskwatim lakes, located downstream of the Rat and Burntwood rivers (Fig. 1). Water from the diverted Churchill River joins the Nelson River at Split Lake, where water levels were affected only very slightly. Three large generating stations (Kettle (1970), creating Stephens Lake; Long Spruce (1977), creating the Long Spruce forebay; and Limestone (1990), creating the Limestone forebay, were constructed on the lower Nelson River (Fig. 1). Upstream on the Nelson River, creation of the Kelsey Generating Station caused the flooding of Sipiwesk Lake in 1961.

Data Collection

Fish were collected using gill nets with panels of various mesh sizes (usually 3.8 to 13.3 cm stretch measure) in the reservoirs and lakes listed in Table 1 (also see Fig. 1). For these survey data, water bodies were sampled as single units except SIL, where two lake basins were sampled (Area 5 and South Bay) (Fig. 1). All fish from a single year were treated as a single sample. Fork length of all fish was measured to the nearest 5 mm, and a sample of epaxial muscle tissue was removed using clean stainless steel instruments, placed in new polyethylene bags, and stored frozen until analysis. Hg concentrations were determined for individual fish using cold-vapour atomic absorption spectrophotometry (Hendzel & Jamieson 1976). Trends are presented for three species of fish: lake whitefish, walleye, and northern pike. Data for other species captured have previously been published in Derksen and Green (1987), Green (1986), Bodaly et al. (1988), Green (1990), and Strange et al. (1991). For survey data, mean Hg concentrations for each location by sample year were calculated for a standardized fork length for each species (350 mm for whitefish, 400 mm for walleye, and 550 mm for pike) by linear interpolation of least-squares regressions of log Hg concentration versus log fork length. The total number of fish sampled and analyzed was 15,484. The number of fish analyzed from each location by year ranged from 3 to 62 and averaged 36 for lake whitefish, ranged from 4 to 271 and averaged 34 for walleye, and ranged from 3 to 280 and averaged 40 for northern pike. Nine of these basins, which had the most complete data, were used to explore temporal trends, and the whole data set was used to examine the relationship between flooding and peak concentrations. Polynomial regressions were used to fit curves to postimpoundment data ($y = a + b_1x + b_2x^2$). Concentrations were considered to have returned to background levels when the lower limit of the 95% confidence interval (CI) for the regression overlapped with the upper limit of the 95% CI for background mean concentrations.

To expand the data set to include data before 1975, Hg concentrations derived from commercial sampling were used if available. Commercial samples were removed periodically from commercial shipments, were classified only to lake of origin, and were not adjusted according to fish size. A sample from at least five fish with a combined weight of at least 6.8 kg was used for each determination. Muscle samples from each fish were combined and homogenized before determination of Hg concentrations. Commercial data were obtained from Canadian Food Inspection Agency, Winnipeg, Manitoba, Canada. The same analytic technique was used to determine Hg concentrations.

Data from pristine lakes of the region were also used to provide a comparative baseline. Lakes in northern Manitoba within the area bounded by 52°29′N to 58°47′N latitude and 93°13′W to 101°41′W longitude were used. Lakes near towns and lakes that had been flooded in the past were excluded, but lakes and lake basins that had preflooding data were included. The number of lakes used to provide this comparison were 13 (lake whitefish), 61 (walleye), and 64 (northern pike). Only samples of a minimum size of 15 fish were used. Mean concentrations, standardized for fish size, were calculated as for survey samples from reservoirs, as given previously.

Results

Postimpoundment Trends in Hg Concentrations

Lake Whitefish

In the two sampled basins of the moderately flooded SIL reservoir, Hg concentrations in lake whitefish increased after impoundment and were highest when first sampled 3 to 5 years after flooding. Peak mean Hg concentrations standardized to 350 mm were 0.24 to 0.26 μg g^{-1} compared with preimpoundment survey sample means of 0.06 to 0.07 μg g^{-1} and compared with a mean of 0.05 μg g^{-1} (range 0.02 to 0.11 μg g^{-1}) from six commercial samples taken from the whole lake before flooding (Table 2 and Fig. 2). Concentrations in both basins decreased significantly thereafter (p = 0.001 to 0.006) and had statistically returned to background concentrations 10 to 12 years after flooding, although they may have still been decreasing as long as 18 years after flooding (Fig. 2 and Table 2).

In the more extensively flooded reservoirs along the Rat–Burntwood diversion route (Issett, Rat, Notigi, Threepoint, and Wuskwatim lakes), peak mean Hg concentrations in lake whitefish were generally similar to those for SIL but took longer to return to background. Means were usually highest 3 to 6 years after flooding when first sampled, although peak levels in Rat Lake did not occur until 10 years after flooding (Fig. 2 and Table 2). Peak concentrations were generally similar to those at SIL (0.23 to 0.25 μg g^{-1}), except for Notigi Lake, which was 0.40 μg g^{-1}. These levels were much higher than preimpoundment mean concentrations of 0.14 μg g^{-1} in Issett Lake and 0.08 μg g^{-1} in Wuskwatim Lake and natural mean concentrations of 0.03 to 0.06 μg g^{-1}. Levels gradually decreased after these peaks (p = 0.0001 to 0.01), becoming statistically similar to background concentrations 11 to 20 years after flooding (Fig. 2 and Table 2). Concentrations in Issett Lake eventually decreased to means that were lower than the preimpoundment value. This may have been caused by downstream migrations of lake whitefish with lower Hg concentrations from SIL and/or an anomalously high preimpoundment mean concentration.

Hg concentrations in lake whitefish from Stephens Lake, an extensively flooded reservoir on the lower Nelson River, were highest when first sampled 13 to 14 years after flooding. The highest mean concentration observed was 0.19 μg g^{-1}, although the actual peak value was likely higher and was missed during the years when no samples were taken (Fig. 2). Concentrations of Hg concentrations in lake whitefish in this reservoir decreased thereafter (p = 0.005) and returned to background 32 years after flooding (Fig. 2 and Table 2).

Hg concentrations in lake whitefish from Split Lake, which started to receive water from the upstream reservoirs in the Rat and Burntwood systems in 1977, were quite stable during the period from 1983 to 2002, although somewhat higher than the expected natural range for this species (Fig. 2).

Walleye Pike

In the SIL reservoir, Hg concentrations in walleye were increased after flooding, reaching mean peak concentrations (standardized to 400 mm) of 0.73 to 0.78 μg g^{-1} 2 to 5 years after flooding compared with a preimpoundment mean range of 0.19 to 0.30 μg g^{-1} from composite commercial samples (Fig. 3). Hg concentrations in this species showed a gradual downward trend thereafter (p = 0.003 for Area 5 and not significant for South Bay) and was similar to background concentrations 10 to 16 years after flooding. However, in both SIL basins, Hg concentrations still appeared to be higher than the preimpoundment range 18 years after flooding.

Peak mean concentrations of Hg in walleye in the reservoirs of the Rat–Burntwood valley were noticeably higher, and return times to background were generally longer, than those observed for the SIL reservoir (Fig. 3 and Table 2). The highest concentrations observed in these four reservoirs were 0.9 to 2.4 μg g^{-1} compared with pre-

Table 2 Peak mean Hg concentrations, time to reach peak concentrations, time for lower 95% CI of postimpoundment polynomial regression to overlap with upper 95% CI of mean Hg concentrations in reference lakes, *p* value of polynomial regression of postimpoundment period, and r^2 value of polynomial regression of postimpoundment period

Reservoir	% Flood	Fish species	Peak Hg (μg/g ww)	Years to peak	Years to return to background	p	r^2
South Indian (South Bay)	20.9	LWF	0.24	≤ 3	10	1×10^{-3}	0.60
		WALL	0.78	2	16	0.87	0.00
		NP	1.10	8	18	0.19	0.19
South Indian (Area 5)	20.9	LWF	0.26	≤ 5	12	6×10^{-3}	0.68
		WALL	0.73	5	10	3×10^{-3}	0.64
		NP	0.75	6	13	3×10^{-4}	0.82
Issett	455.4	LWF	0.24	≤ 3	11	4×10^{-3}	0.63
		WALL	1.52	≤ 3	14	1×10^{-3}	0.67
		NP	0.85	8	19	0.03	0.42
Rat	159.8	LWF	0.25	10	20	2×10^{-4}	0.77
		WALL	2.38	≤ 4	21	1×10^{-4}	0.69
		NP	1.69	≤ 4	23	1×10^{-6}	0.89
Notigi	248.6	LWF	0.40	≤ 6	12	6×10^{-3}	0.81
		WALL	2.05	6	13	0.03	0.41
		NP	2.59	6	22	2×10^{-3}	0.67
Threepoint	47.7	LWF	0.23	≤ 4	20	1×10^{-4}	0.75
		WALL	1.65	6	21	2×10^{-5}	0.79
		NP	1.76	6	19	5×10^{-6}	0.86
Wuskwatim	48.1	LWF	0.25	≤ 5	17	0.01	0.76
		WALL	0.94	3	n/a[a]	0.31	0.08
		NP	1.42	7	16	0.07	0.36
Stephens	236.6	LWF	0.19	14	32	5×10^{-3}	0.56
		WALL	1.76	≤ 11	19	5×10^{-4}	0.68
		NP	1.04	≤ 13	23	4×10^{-6}	0.92

LWF = lake whitefish; NP = northern pike; WALL = walleye

[a] Lower 95% CI of polynomial regression did not exceed upper 95% CI for mean Hg concentration of reference lakes

impoundment means of 0.25 to 0.44 μg g^{-1} in Wuskwatim Lake and a range of 0.35 to 0.47 μg g^{-1} in natural lakes in the region. These peak concentrations were observed within 6 years after impoundment. Levels decreased thereafter (p = 0.00005 to 0.03 except for Wuskwatim Lake, where p = not significant), and mean concentrations were statistically within background range 13 to 21 years after flooding (Table 2).

In Stephens Lake, Hg concentrations in walleye were highest when first sampled 11 years after impoundment (Fig. 3 and Table 2). Mean concentrations gradually decreased thereafter (p = 0.0005) and were statistically within the natural range 19 years after flooding.

Hg concentrations in walleye from Split Lake were quite stable during the 33-year period of record (1970 to 2002). Means generally ranged between approximately 0.3 and 0.7 μg g^{-1}, with a decreasing trend during the period from 1990 to 2002 to concentrations of approximately 0.2 μg g^{-1} (Fig. 3). No obvious increases occurred after 1977 when the full flow of the diverted Churchill River brought water from upstream reservoirs. However, Hg concentrations in walleye in 1982 were the highest recorded during the 26-year record.

Northern Pike

Mean Hg concentrations in northern pike in the SIL reservoir increased after flooding and peaked 6 to 8 years after impoundment (Fig. 4 and Table 2). The highest mean concentrations observed in SIL (standardized to 550 mm) were 0.75 to 1.1 μg g^{-1} compared with levels before flooding, which were 0.26 to 0.32 μg g^{-1} (from composite commercial samples). Hg concentrations in northern pike from SIL decreased (p = 0.003 for Area 5, but p = not significant for South Bay) to levels that were within the natural range 13 to 16 years after flooding, although northern pike from South Bay were still higher than preimpoundment concentrations (Fig. 4 and Table 2).

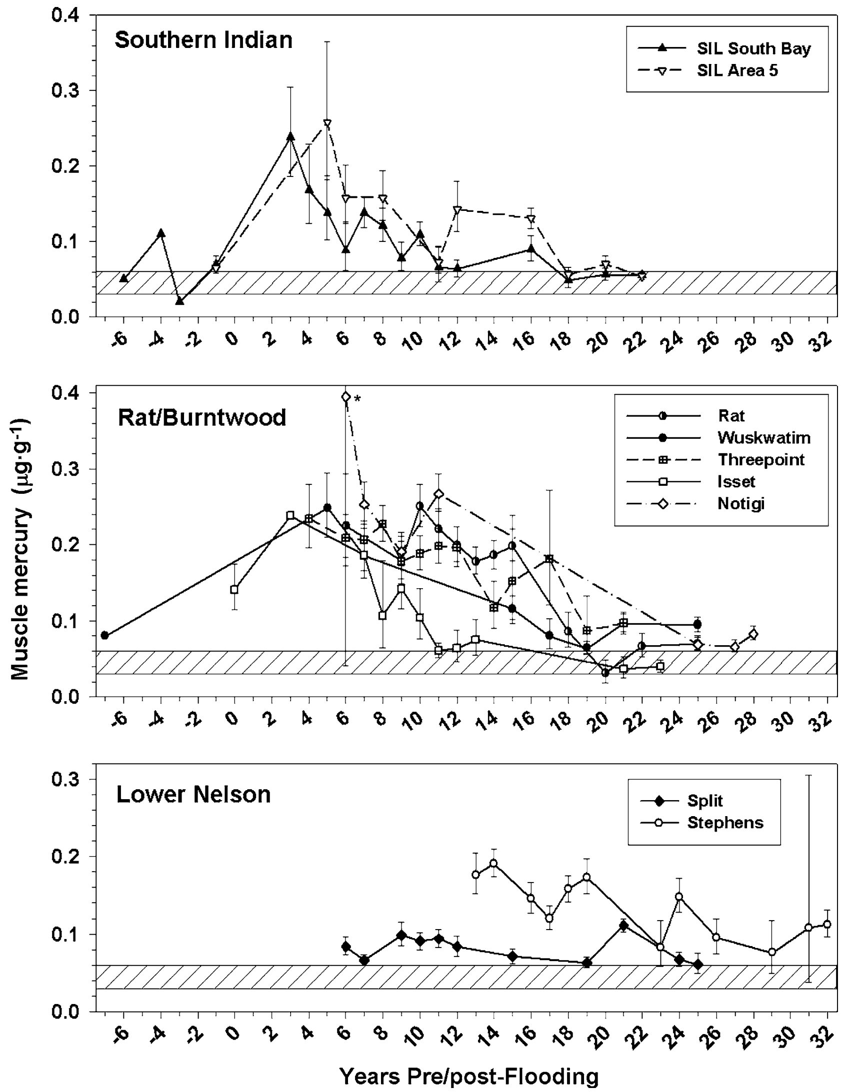

Fig. 2 Mean concentrations (±95% CI) of total Hg (µg g^{-1} ww) in the muscle of lake whitefish from hydroelectric reservoirs of northern Manitoba. Upper panel: Basins in SIL (South Bay, Area 5). Middle panel: Basins on the Rat and Burntwood rivers (Issett, Rat, Notigi, Threepoint, and Wuskwatim lakes). Lower panel: Basins on the lower Nelson River (Split and Stephens lakes). Yearly means without confidence bars are means of ≥1 commercial samples (see Methods). The band of concentrations is the 95% CI for mean concentrations in natural lakes of the region (see Methods). Asterisk indicates confidence interval of range of axis; the upper CI for lake whitefish from Notigi Lake 6 years after flooding was 3.8 µg g^{-1}

In reservoirs of the Rat–Burntwood valley, Hg concentrations in northern pike reached peak mean values of 0.85 to 2.6 µg g^{-1} compared with natural mean levels of 0.36 to 0.47 µg g^{-1} (Fig. 4 and Table 2). These peak values were much higher than in the SIL reservoir. Highest concentrations were seen ≤ 4 to 8 years after flooding. Hg concentrations in these reservoirs had decreased ($p = 0.000005$ to 0.03, but p = not significant for Wuskwatim) to within background concentrations 16 to 23 years after flooding in the various reservoirs, although it was still decreasing in two of the water bodies when within the range of background concentrations.

Hg concentrations in northern pike in Stephens Lake were highest when first sampled 13 years after flooding at 1.0 µg g^{-1} (Fig. 4 and Table 2). Mean concentrations decreased irregularly during the next 10 years (p = 0.000004) until they were within the natural range for the area 23 years after flooding.

In Split Lake, mean Hg concentrations in northern pike were quite stable at 0.26 to 0.52 µg g^{-1} from 1970 to 1990. Concentrations were consistently lower (and lower than the natural range) between 1996 and 2002 (Fig. 4). Similar to walleye, there was no obvious increase after the 1977 diversion of the Churchill River, although Hg concentrations were highest in 1982.

Relation Between Hg Concentrations and Amount of Flooding

Amount of flooding appears to be an important factor influencing postimpoundment Hg concentrations (Fig. 5). Peak mean Hg concentrations in northern pike and walleye increased sharply with increasing amount of flooding but leveled off at approximately 100% flooding. Hg concentrations in reservoirs might be expected to be a function of relative surface areas (flooded vs. unflooded) or relative

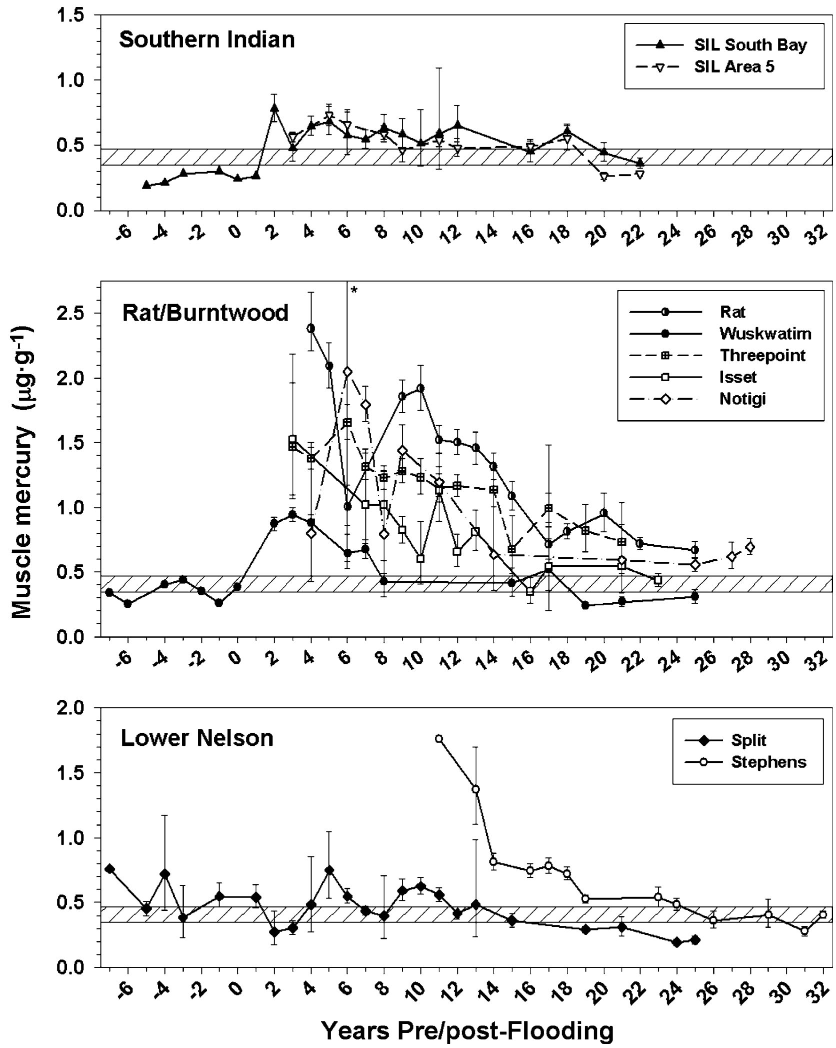

Fig. 3 Mean concentrations (±95% CI) of total Hg (µg g^{-1} ww) in the muscle of walleye from hydroelectric reservoirs of northern Manitoba. Upper panel: Basins in SIL (South Bay, Area 5). Middle panel: Basins on the Rat and Burntwood rivers (Issett, Rat, Notigi, Threepoint, and Wuskwatim lakes). Lower panel: Basins on the lower Nelson River (Split and Stephens lakes). Asterisk indicates confidence interval of range of axis; the upper CI for walleye from Notigi Lake 6 years after flooding was 7.2 µg g^{-1}

volumes (flooded volume vs. preflooding volume); however, equations assuming these relationships did not describe the data sets well, with R^2s ranging from only 7% to 24%. An exponential model did describe the data well. The equation was as follows: $y = y_0 + a\,(1–e^{-bx})$, where y_0 is the y intercept, and $y_0 + a$ is the asymptotic value. The parameters were as follows:

Species y_0 a b r^2 p

Northern pike 0.450 1.127 0.034 0.886 <0.01

Walleye 0.501 1.137 0.024 0.916 <0.01.

Therefore, the asymptotic values were 1.58 (northern pike) and 1.64 (walleye). Y intercepts corresponded well to those actually determined for reference lakes in the area (Fig. 5). A similar relationship was observed for lake whitefish, with an asymptotic concentration of approximately 0.25 µg g^{-1}.

Upstream flooding tended to increase Hg concentrations in fish in downstream reservoirs, but this effect was quite variable (Fig. 5). For lake whitefish, four of six reservoirs with no flooding upstream had lower-than-expected concentrations of Hg. For walleye and northern pike, five of seven reservoirs with no flooding upstream had lower-than-expected Hg concentrations.

Discussion

The long-term scale and relative completeness of this data set on Hg concentrations in boreal reservoirs allowed the time course for changes in Hg concentrations in fish to be defined. Increases in Hg concentrations took place in northern Manitoba reservoirs in all fish species examined. Peak values of 0.2 to .4 µg g^{-1} in lake whitefish, a benthic invertebrate feeder, and 0.7 to 2.4 µg g^{-1} in piscivorous walleye and northern pike were observed. Peak values were usually observed within 10 years of flooding for all species, but the data were often incomplete in the early years of existence for many reservoirs. However, it did appear that

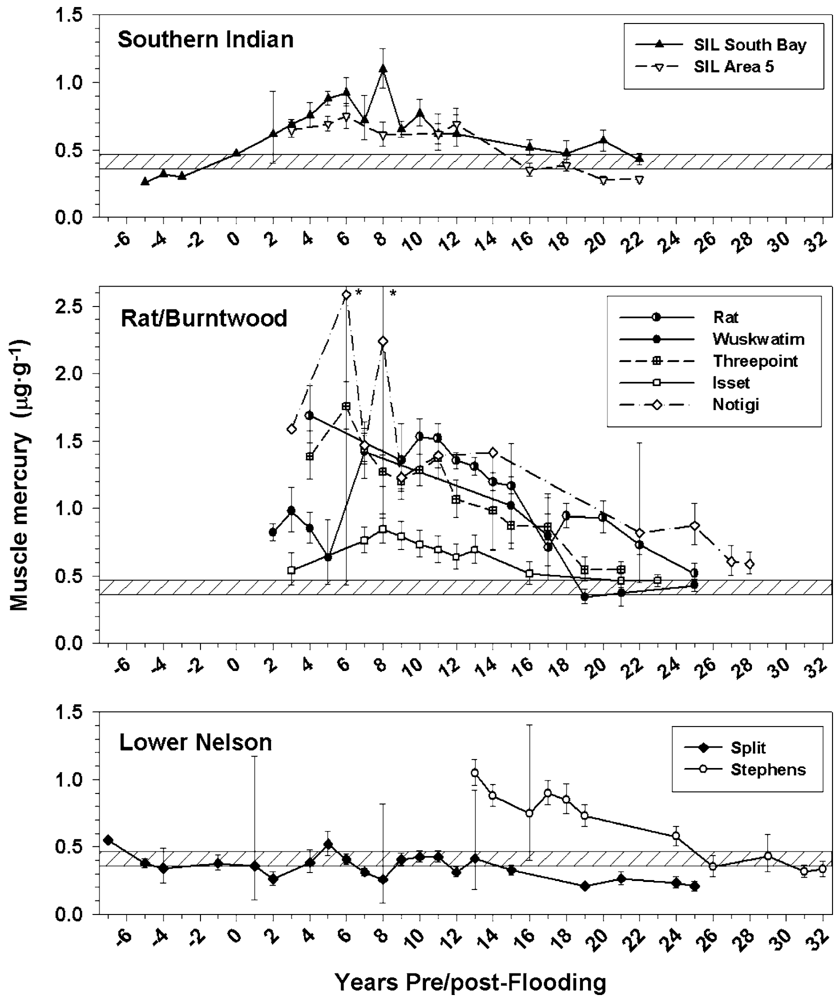

Fig. 4 Mean concentrations (±95% CI) of total Hg (µg g^{-1} ww. in the muscle of northern pike from hydroelectric reservoirs of northern Manitoba. Upper panel: Basins in SIL (South Bay, Area 5). Middle panel: Basins on the Rat and Burntwood rivers (Issett, Rat, Notigi, Threepoint, and Wuskwatim lakes). Lower panel: Basins on the lower Nelson River (Split and Stephens lakes). Asterisks indicate confidence interval of range of axis; the upper CI for northern pike from Notigi Lake 6 years after flooding was 15.5 µg g^{-1} and for Notigi Lake 8 years after flooding was 5.4 µg g^{-1}

the time to reach peak concentrations was shortest for lake whitefish, intermediate for walleye, and longest for northern pike.

The amount of time required for Hg concentrations to return to preimpoundment levels or levels seen in natural lakes of the region was, with one exception, 10 to 20 years for lake whitefish, supporting our hypothesis that return times would always be <20 years for nonpiscivorous species. For walleye and northern pike, return times ranged from 10 to 23 years. Therefore, our hypothesis that Hg concentrations would be increased in piscivorous species for a minimum of approximately 20 years was not supported, although in many of the reservoirs with shorter return times, mean concentrations were still decreasing after they were statistically within the range of background concentrations.

Studies of Hg concentrations in newly flooded reservoirs in other boreal regions generally found longer return times compared with the present study. Schetagne and Verdon (1999) studied the evolution of Hg concentrations in fish in the LaGrande Complex reservoirs of northern Quebec. They found that Hg concentrations in lake whitefish were highest 4 to 9 years after flooding at concentrations of 0.35 to 0.55 µg g^{-1} and had returned to background concentrations approximately 10 to >25 yrs after flooding. In predatory fish (northern pike), levels peaked 10 to 13 yrs after impoundment and were not predicted to return to background levels until 20 to 30 years after flooding. In Finnish reservoirs, peak concentrations of Hg concentrations, 0.8 to 1.9 µg g^{-1}, occurred in northern pike 3 to 9 years after flooding (Verta & Porvari 1995). Decreases took place after peak concentrations were seen, but background levels had not been reached within 12 to 26 years after flooding (Verta & Porvari 1995). Hg concentrations in fish in reservoirs in Manitoba were generally lower than observed in northern Quebec but were similar to those in Finland. Increases in Hg concentrations in fish have been observed in temperate and tropical reservoirs, but these increases were less than in the boreal zone (Abernathy & Cumbie 1977; Cox et al. 1979; Yingcharoen & Bodaly 1993).

Aboriginal peoples in boreal regions can depend on fish for food and cultural activities, and the increased concen-

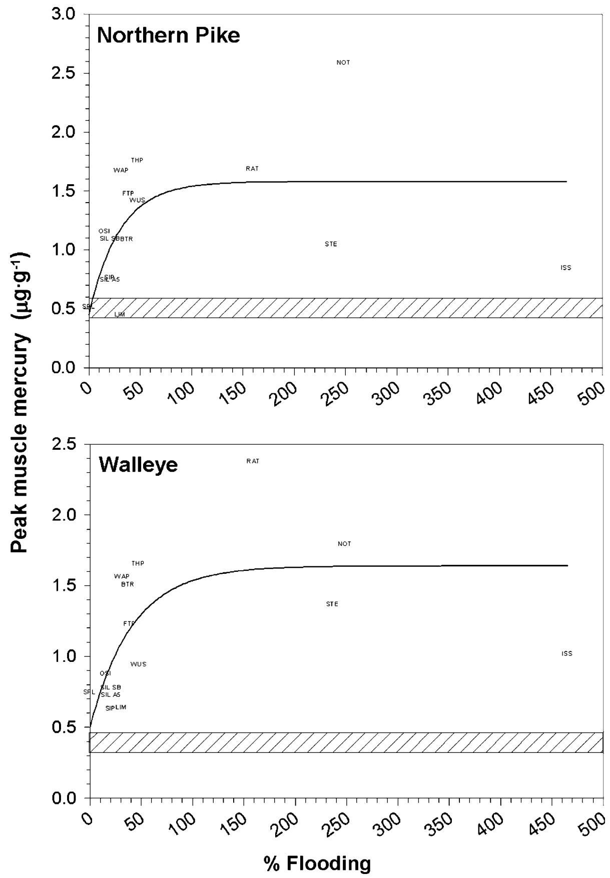

Fig. 5 Maximum observed muscle Hg concentrations in fish from northern Manitoba reservoirs versus degree of flooding. Upper panel: Northern pike. Lower panel: Walleye. Fitted lines assume an exponential increase to a maximum as described by the equation: $y = y_0 + a\,(1\text{–}e^{-bx})$. The band of concentrations is the 95% CI for mean concentrations in natural lakes of the region (see Methods)

trations of Hg observed in hydroelectric reservoirs can cause significant impacts. Hg concentrations in predatory fish in boreal reservoirs are commonly ≥1 to 2 µg g^{-1}, commonly seen only at sites subject to point source pollution of Hg. These levels are high compared with the Canadian limit for commercial sale, 0.5 µg g^{-1}, and the suggested limit for frequent consumption, 0.2 µg g^{-1}. The United States Environmental Protection Agency recently declared a limit for safe exposure for humans of 0.1 µg/kg body weight/d that at the 1 µg g^{-1} concentrations frequently seen in boreal reservoirs translates to only 50 g fish/wk or approximately 0.1 pound/wk (for a 70 kg adult).

The observed increases of Hg concentrations in fish from the hydroelectric reservoirs of northern Manitoba are consistent with observations on the production of significant amounts of new MeHg in the flooded zones of new boreal reservoirs. Increased Hg concentrations in the food chains of boreal reservoirs have been related to increased production of MeHg stimulated by the decomposition of flooded organic matter (Bodaly et al. 1997, 2004; Grondin et al. 1995; Kelly et al. 1997; Lucotte et al. 1999). The relation between amount of flooding and Hg concentrations in fish in new reservoirs presented here is also consistent with the production of new MeHg in the flooded zone of new reservoirs and confirms models, such as those described by Johnston et al. (1991), that are based on the relationship between flooding and Hg concentrations in fish. However, the relation between amount of flooding and peak Hg concentrations in fish was not based on the ratio of flooded to unflooded reservoir surface area or volume, as expected. Rather, Hg concentrations in fish reached an asymptote at approximately 100% flooding. This asymptotic relationship may be related to the fact that once a reservoir is flooded extensively, the littoral zone, with its higher temperatures and consequently higher rates of organic carbon decomposition and Hg methylation, would be composed entirely of flooded terrestrial area, and MeHg production would be at a maximum for these systems. Therefore, further flooding may not result in higher Hg concentrations in fish.

Differences in the postimpoundment time course and peak Hg concentrations in fish from northern Manitoba reservoirs appear to reflect differences in feeding habits of the fish species studied. Predatory fish (walleye and northern pike) had higher concentrations and longer lag times than lake whitefish, consistent with their higher position in the food chain. The invertebrate feeding lake whitefish had peak Hg concentrations of approximately 0.2 to 0.4 µg g^{-1} wet weight (approximately 1.0 to 2.0 µg g^{-1} dry weight (dw) compared with concentrations in piscivorous fish of up to 2 µg g^{-1} (10 µg g^{-1} dw) or higher. Tremblay (1999) found concentrations of MeHg in invertebrates from northern Quebec reservoirs to range between 45 to 650 ng g^{-1} dw, but most groups in most reservoirs had concentrations <200 ng g^{-1}. Hall et al. (1998) found that MeHg in invertebrates in an experimental wetland reservoir were similar to those reported from Quebec: means 190 ng g^{-1} dw in predators, 176 ng g^{-1} in predators and herbivores, and 72 ng g^{-1} in collector shredders. In zooplankton, MeHg in newly flooded reservoirs in northern Quebec was 350 to 500 ng g^{-1} dw (Tremblay 1999). Paterson et al. (1998) and Peech Cherewyk (2002) found MeHg in zooplankton in experimental peatland and upland reservoirs to be generally in the range of 200 to 600 ng g^{-1} dw, similar to the reservoirs of northern Quebec. Therefore, a clear biomagnification of MeHg in the food chains of boreal reservoirs is evident as it is for other freshwater systems.

An important finding this and similar studies is that although the peak of production of new MeHg in boreal reservoirs is reached within a few years of flooding, Hg concentrations in predatory fish will take up to 10 years to reach peak levels and up to 3 decades to return to background concentrations. Bodaly et al. (1997) noted that MeHg in water and zooplankton are increased in reservoirs for <10 years after flooding. For experimental boreal upland reservoirs, Hall et al. (2005) found that MeHg production peaked in the second year of flooding. In an experimental wetland boreal reservoir, St. Louis et al. (2004) found that MeHg production was highest in the first year of flooding, although concentrations were still increased 9 years after flooding. Mercury concentrations in zooplankton from the pelagic zones of northern Quebec reservoirs were similar to natural lakes 8 years or less after flooding, whereas Hg concentrations in zooplankton and benthic invertebrates from littoral zones of northern Quebec reservoirs were still increased 16 years after flooding (Tremblay 1999). These observations were consistent with those of Lucotte et al. (1999), who found that MeHg in flooded soils in northern Quebec reservoirs increased for ≥10 in shallow zones. A relatively short pulse of increased MeHg in reservoirs of <5 years is apparently sufficient to fuel an extended period of increase of Hg concentrations in predatory fish because there is a long lag between MeHg in water and invertebrates and Hg concentrations in larger, older fish.

A ''downstream'' effect of reservoir creation on Hg concentrations in fish in receiving waters has been demonstrated in other studies. Studies on northern Quebec reservoirs found downstream transport of MeHg in zooplankton and other drifting organisms (Tremblay 1999; Schetagne & Verdon 1999) and have quantified the mass balance of Hg exported downstream (Schetagne et al. 2000). Experimental flooding studies at the Experimental Lakes Area also demonstrated significant increases in the downstream transport of MeHg (Kelly et al. 1997; St. Louis et al. 2004; Hall et al. 2005). In northern Manitoba reservoirs, there appeared to be downstream effects, but the amount of variation was large, and not all reservoirs with upstream flooding had higher-than-expected Hg concentrations in fish. In Split Lake, there was no apparent effect of upstream flooding on Hg concentrations in fish. This water body was apparently too far downstream from the nearest reservoir (135 km) to show downstream effects, although downstream effects of the Caniapiscau Reservoir (up to 275 km) in northern Quebec were seen in Hg concentrations in fish (Schetagne & Verdon 1999).

This article has synthesized a large amount of data concerning the time course of increased Hg concentrations in fish in the boreal reservoirs of northern Manitoba. Monitoring ≥25 years has been required to see a return to background concentrations in some reservoirs. Hg concentrations in these reservoirs did, however, eventually resemble those in natural lakes or the lakes flooded to create the reservoirs. This indicates that old boreal reservoirs are similar to natural lakes in terms of Hg cycling and bioaccumulation. The relationships between degree of flooding and Hg concentrations in fish and the downstream impact of flooding were highly variable and appear to deserve future study.

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