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Fish mercury levels in relation to characteristics of hydroelectric reservoirs in Newfoundland, Canada

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Abstract. Mercury levels in fish have been demonstrated to increase after impoundment with augmented levels of mercury predicted to decline as the reservoir ages. Previous research in Newfoundland predicted return rates in the order of 10 to 12 years for landlocked Atlantic salmon or ouananiche (*Salmo salar*) and 7 years for brook trout (*Salvelinus fontinalis*). In order to test the validity of these predictions on a broader spatial and temporal scale, and develop more generally predictive 'models', mercury levels in three fish species were studied in 16 older Newfoundland hydroelectric reservoirs of various age (32 to 95 years) and area flooded (21 to 13,000 ha).

Mercury concentrations were standardized to fish length and correlated with physical, chemical, and biological characteristics of the sampling sites. Standard length mercury levels ranged from 0.23 to 0.86 ppm in ouananiche, 0.13 to 0.59 ppm in brook trout, and 0.22 to 0.72 in arctic charr (*Salvelinus alpinus*). Fish in excess of the Canadian Safety Limit (0.5 ppm) were collected from 14 of 16 sites for ouananiche, 8 of 17 sites for brook trout, and 3 of 7 sites for arctic charr, including control lakes. Standard length fish mercury levels were correlated with reservoir age and ($\log_{10}$) area flooded for ouananiche and with pH for arctic charr. A multiple regression model was developed relating standard length mercury in ouananiche with reservoir age and $\log_{10}$ of the flooded area. There were no apparent relationship between reservoir characteristics and brook trout mercury concentrations. Based on this analysis, it is not possible, at present, to develop generally predictive models for all species found in Newfoundland impoundments.

Introduction

Over the last 20 years, elevated mercury levels have been reported in fish from hydroelectric reservoirs while fish in adjacent un-impounded lakes have not shown signs of increased mercury burden. It is generally accepted that mercury present in the terrestrial environment prior to flooding is released as a result of inundation and is biologically available (Bodaly et al. 1984; Hecky et al. 1987; Morrison & Thérien 1991; Montgomery et al. 1995). After inundation, mercury levels in fish first increase and then decline as the reservoir ages. Scientists, regulatory agencies and utilities have been interested in developing models to predict the time required for mercury in fish to return to pre-impoundment levels. These models have largely been based on characteristics such as 'area flooded' and 'age of reservoir', however many other factors have been postulated to influence return time, such as pH, dissolved organic carbon (DOC), and operational characteristics of reservoirs (Wren & MacCrimmon 1983; Verta et al. 1986; McMurty et al. 1989; Wiener et al. 1990). Further, characteristics of fish species in the reservoirs, in particular longevity and trophic status, will also influence temporal evolution of mercury levels (Anderson et al. 1994).

Several estimates exist predicting return time, ranging from estimates as low as 3–5 years in Northern Manitoba reservoirs (Jackson 1988) to 20–30 years in Quebec (Verdon et al. 1991) and Finnish Reservoirs (Verta et al. 1986). In Newfoundland (NF), Canada return periods in the order of 10 to 12 years for ouananiche (*Salmo salar*) and 7 years for brook trout (*Salvelinus fontinalis*) have been predicted (Scruton et al. 1994) for three recently (since 1980) flooded hydroelectric reservoir systems.

There are currently a large number of proposals for hydroelectric development in Newfoundland and there is a need to be able to predict fish mercury levels for a variety of types and scales of development in order to assess potential environmental effects. The aim of this current study is to develop a more generally applicable model for prediction of mercury return times in fish from insular Newfoundland hydroelectric reservoirs based on physical, chemical, and biological characteristics of impoundments. To achieve this, mercury levels in fish were studied in a number of older, widely distributed, hydroelectric reservoirs of various age (32–95 years) and area flooded (21 to 13,000 ha). These data compliment ongoing monitoring of recent ($<$20 years) hydroelectric developments being conducted by the Department of Fisheries and Oceans and Newfoundland and Labrador Hydro.

Materials and methods

Sampling sites

Reservoirs (16) and control ponds (3) were selected to represent a range in age and size (Table 1) and were geographically distributed throughout insular Newfoundland (Figure 1). Five of the reservoirs (Hinds Lake, Great Burnt Lake, Cold Spring Pond, Long Pond, Cat Arm) and two control ponds (Eclipse Pond, Rocky Pond) are part of an ongoing monitoring program conducted by the Canadian Department of Fisheries and Oceans (DFO) and Newfoundland and Labrador Hydro (NLH) and have previously been studied (Scruton et al. 1994). The remaining 11 reservoirs and one additional control pond had not previously been studied.

Table 1. Location, age (as of data used), area flooded, mean depth, and fish species sampled from the study sites.

Site	Location	Age (yrs)	Area flooded (ha)	Mean depth (m)	No. of each species BT	OU	AC
Middle Gull Pond (C)	47°21.3′ N, 53°18.3′ W	–	–	N/A	26	26	0
Eclipse Pond (C)	48°60.0′ N, 56°46.8′ W	–	–	N/A	20	26	0
Rocky Pond (C)	48°10.5′ N, 56°23.0′ W	–	–	N/A	39	40	0
Cochrane Pond	47°27.9′N, 52°51.5′ W	85	30	2.4	21	21	0
Bay Bull's Big Pond	47°24.7′ N, 52°47.3′ W	95	175	7	20	0	0
Mobile First Pond	47°15.3′ N, 52°54.5′ W	44	40	N/A	20	21	0
Mobile Big Pond	47°15.9′ N, 52°59.9′ W	55	378	8	27	23	0
Mount Carmel Pond	47°08.9′ N, 53°04.7′ W	42	140	9.5	30	14	0
Trinity Pond	48°24.6′ N, 53°27.8′ W	40	95	4	0	17	30
Sandy Lake	49°14.7′ N, 56°59.6′ W	32	75	2	27	22	0
Hind's Lake	48°59.7′ N, 57°03.1′ W	16	2,141	N/A	14	31	0
Red Indian Lake	48°48.1′ N, 56°34.2′ W	86	N/A	N/A	18	17	5
Joe Dennis Pond	48°23.0′ N, 58°12.3′ W	50	21	4.8	26	0	0
Granite Lake	48°10.5′ N, 56° 59.2′ W	24	8,000	N/A	10	36	25
Meelpaeg Lake	48°19.6′ N, 56°14.2′ W	26	32,800	N/A	0	34	27
Great Burnt Lake	48°19.6′ N, 56°14.2′ W	8	2,500	10	28	26	0
Cold Spring Pond	48°11.4′ N, 56°17.4′ W	10	1,000	8	48	31	10
Long Pond	48°05.5′ N, 55° 49.5′ W	26	13,000	16	33	83	22
Cat Arm	50°04.0′ N, 56°56.5′ W	9	4,300	18	58	0	114

C = control pond
BT = brook trout
OU = ouananiche
AC = arctic charr

Water quality

Samples were taken to investigate water chemistry and relative productivity of the study sites to determine if these characteristics were related to mercury levels in post-impoundment fish. Water samples were collected during the summer of 1995 at the centre at each site utilizing a Nisken bottle and then transferred to acid-washed collection vessels. All samples taken were analysed for dissolved oxygen (DO), total organic carbon (TOC), total organic nitrogen (TON), pH, nitrates, total organic phosphate (TOP), and chlorophylls (Chl). Dissolved oxygen was determined using Winkler titration and TOP with a modification of methods described in Murphy & Riley (1962) and Menzel & Corwin (1965). Nitrates were determined with cadmium reduction as outlined in Stainton et al. (1977). Total organic carbon and TON were both determined with a CHN analyser and together used to determine the carbon:nitrogen ratio (C:N). Chlorophyll was determined by fluorometer in accordance with

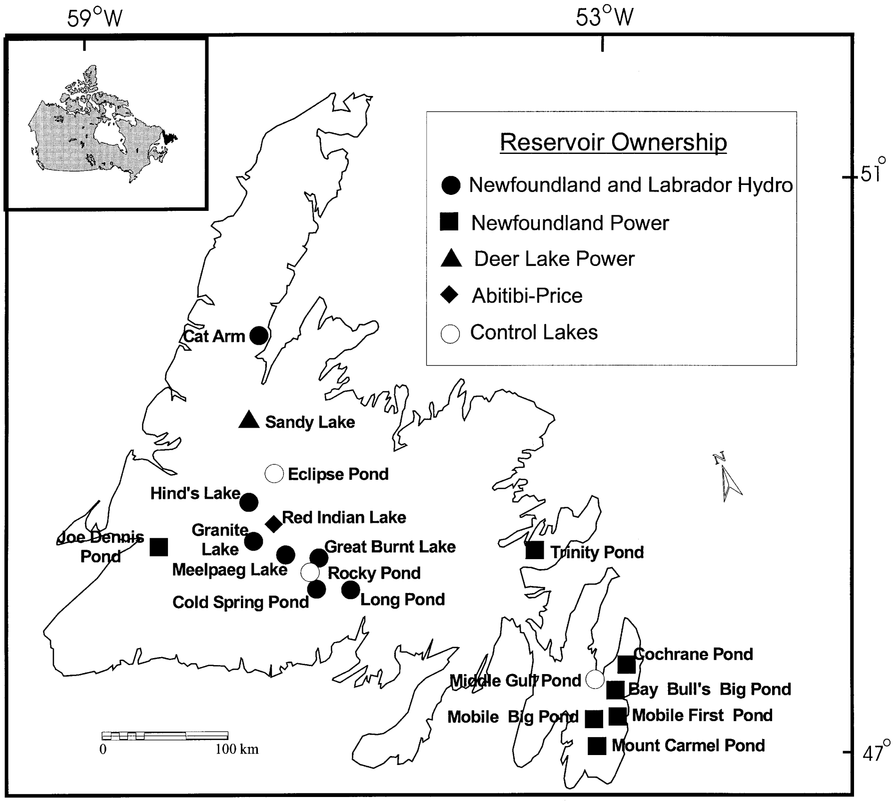

Figure 1. Location of sampling sites, including reservoir ownership, on the island of Newfoundland.

Strickland & Parsons (1972). Conductivity and pH were determined directly on site using field meters (Hanna Instruments conductivity meter, model HI8733; Piccolo ATC pH meter, respectively). Secchi depth was determined using a standard 30 cm secchi disc.

Fish and mercury analysis

Three species of fish in insular Newfoundland, landlocked Atlantic salmon or ouananiche (*Salmo salar*), brook trout (*Salvelinus fontinalis*), and arctic charr (*Salvelinus alpinus*) were collected from the study sites by gill netting supplemented with angling in 1994 and 1995. A minimum of thirty individuals of each species present at a sampling site, where possible, were collected according to a length stratified protocol (Table 2). All fish collected were sized (fork length [FL]). A fillet was taken from the left dorsal region of each specimen and frozen for subsequent mercury analysis. For individ-

Table 2. Length stratified sampling protocol utilized for fish collection in the study sites.

Number to be sampled	Species		
	Ouananiche	Brook trout	Arctic charr
5	<100 mm	<100 mm	<120
5	101–200	101–140	121–150
5	201–300	141–180	151–180
5	301–400	181–220	181–210
5	401–500	221–260	211–240
5	>501	>261	>241

uals less than 10 cms, the entire fish was frozen. Analysis for mercury was carried out at the DFO's Inspection Laboratory using cold vapour atomic absorption spectrophotometry with a detection limit of 0.01 ppm. Laboratory quality assurance included duplicate analyses as well as analysis of blanks and National Bureau of Standard's standard reference materials.

Data analysis

A standardized length was selected as the modal length for the combined sample (all reservoirs) since this size would be that most frequently encountered by recreational anglers. Mercury content in fish from each of the study sites were regressed against fork length. In cases where conditions of normality and homoscedasticity were not met, data were either $\log_{10}$ or square transformed. The 'standardized' mercury content for each species at each site was determined from the regression equation (Table 4). Where fork length was not a significant predictor of mercury concentration (3 cases) the mean Hg was subsequently used in the analyses. 'Standardized' mercury body burden and mean Hg levels were then correlated with the physical and chemical characteristics of the reservoirs. Control sites were excluded from this analysis. Those significant correlates ($p < 0.05$) were then placed in further regression analysis, multiple or otherwise, based on the number of significant correlates.

Results

Water quality

The physical and chemical characteristics of the sampling sites demonstrated a relatively narrow range in variation (Table 3). Light penetration (secchi

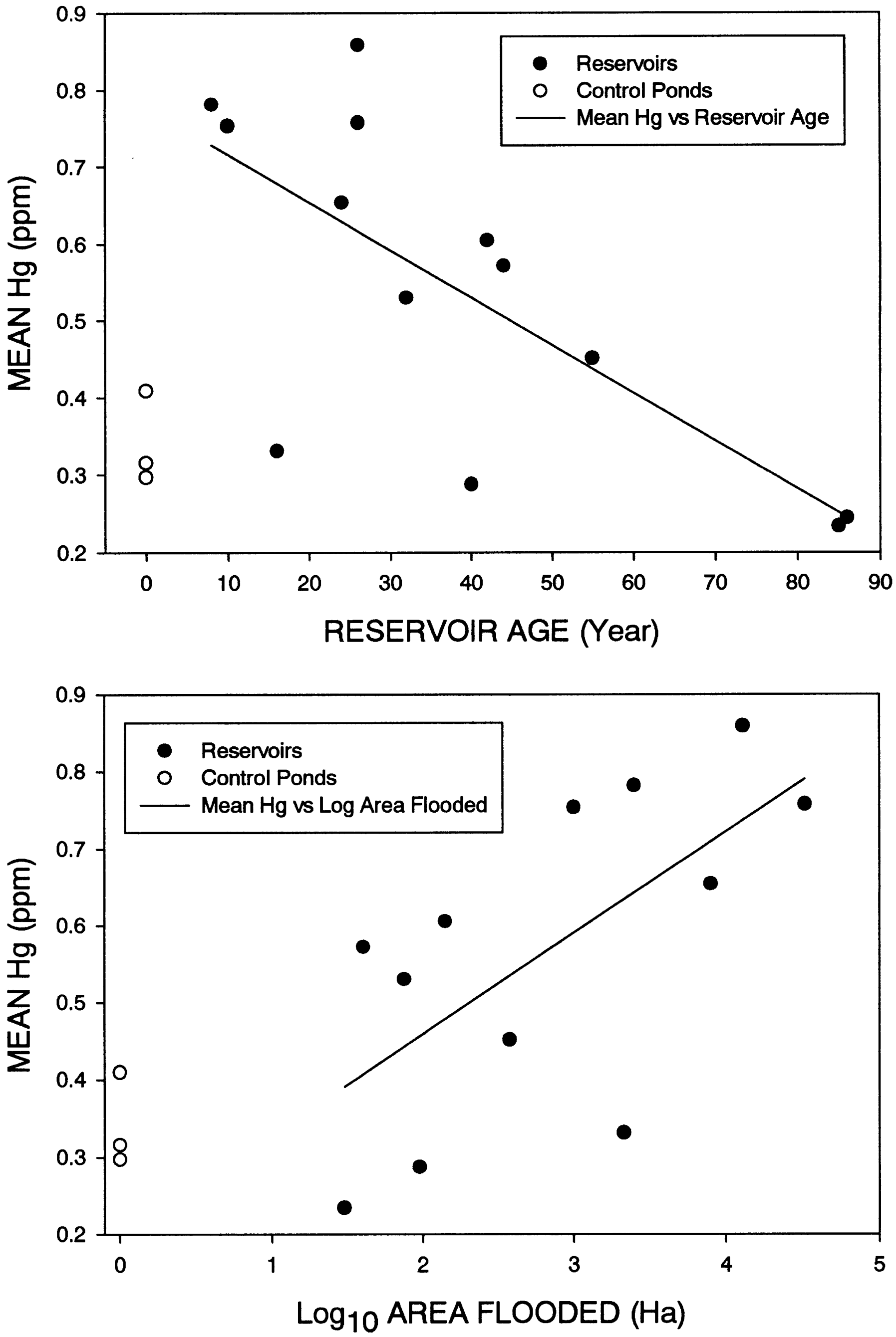

Figure 2. Mean mercury concentrations for ouananiche in relation to age of reservoir and $\log_{10}$ of the flooded area. Regression lines are also shown for reference.

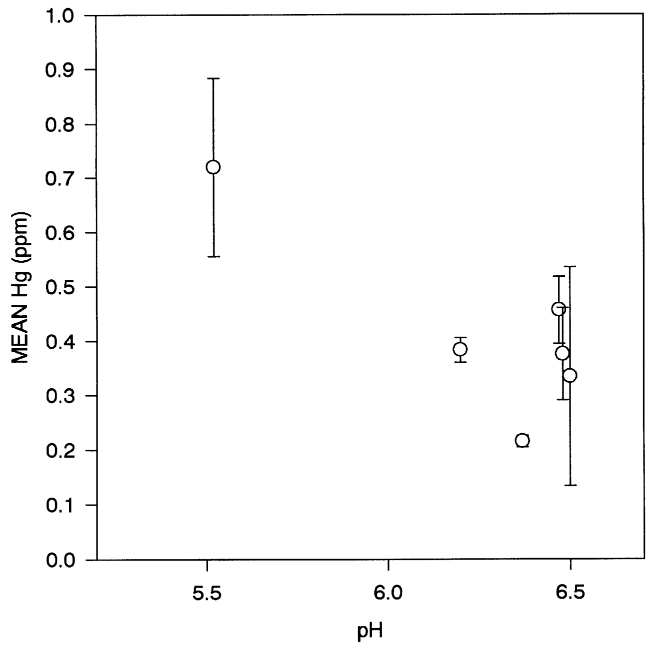

Figure 3. Mean mercury concentrations for arctic charr in relation to pH of the reservoirs.

depth) ranged from 2.3 to 10.0 m. Study sites ranged from moderately acidic (pH 5.52) to basic (pH 7.46) with a mean of pH 6.53. Study lakes were low in conductivity with values ranging from 10.1 to 55.2 μS·cm^{-1}. Nitrate values varied from 0.9 to 30.5 μg·L^{-1}. Total phosphorous levels were near or below detection limits. Dissolved oxygen ranged from 8.5 to 10.03 mg·L^{-1} (mean of 9.12). Chlorophyll levels ranged from 0.09 to 0.29 μg·L^{-1} while TOC ranged from 0.07 to 0.22 μg·ml^{-1}. The carbon to nitrogen ration (C:N) ranged from 7.43 to 20.23.

Fish mercury levels

Summary of fish mercury data, including mean values, standardized mean values and regression equations, and number of fish at each site above the Canadian Safety Limit of 0.5 ppm is provided in Table 4. All three fish species included in this study were not distributed throughout all the study sites. Ouananiche were found in sixteen of the nineteen sites, brook trout in 17, and arctic charr in only 7 water bodies. Only 5 arctic charr of similar length were collected from Red Indian Lake, consequently these data were not included in the analyses. Arctic charr were also not sampled from either of the 3 control ponds, consequently pre-impoundment data (1982) from Cat

Table 3. Physical and chemical characteristics of the sampling sites. Data for Rocky Pond is not available.

Site	Secci depth (m)	pH	Conduct. (μscm^{-1})	Nitrates (μg/l)	Total phos. (μg/l)	Dissolved O_2 (mg/l)	Chlorophyll (μg/l)	TOC (μg/l)	TON (μg/l)
Middle Gull Pond (C)	10	7.46	26.8	2.2	$<$10	9.55	0.09	221.8	25.8
Eclipse Pond (C)	3.75	5.83	10.1	1.2	$<$10	10.03	0.24	506.3	46.5
Cochrane Pond	3.53	7.32	55.2	1.08	11	8.63	0.19	608.3	62.3
Bay Bull's Big Pond	4.5	7.15	53	7.5	$<$10	9.48	0.27	363.0	25.2
Mobile First Pond	5.83	6.58	25	12	$<$10	9.23	0.12	299.0	25.5
Mobile Big Pond	4.5	6.83	24.4	29.9	$<$10	8.95	0.10	334.5	45.0
Mount Carmel Pond	4.2	6.48	25.8	0.9	10	9.17	0.29	474.5	46.5
Trinity Pond	3.35	6.37	37.5	1.16	$<$10	8.83	0.24	455.5	44.9
Sandy Lake	2.3	6.39	22.1	30.1	$<$10	9.00	0.16	561.5	27.8
Hind's Lake	3	6.16	14.1	29	$<$10	9.23	0.20	340.0	27.8
Red Indian Lake	N/D	6.45	21.3	30.5	$<$10	9.45	0.11	326.3	21.5
Joe Dennis Pond	3.8	6.5	23.2	27.8	$<$10	8.50	0.17	403.8	28.0
Granite Lake	3.0	6.2	13.6	26.1	$<$10	8.85	0.11	315.8	28.0
Meelpaeg Lake	3.5	6.48	13.2	29.0	23	9.45	0.21	410.8	36.5
Great Burnt Lake	3.8	6.61	13.6	27.7	22.7	9.15	0.20	333.8	31.3
Cold Spring Pond	3.5	6.5	14.5	29.8	$<$10	8.80	0.19	438.3	40.5
Long Pond	4.5	6.47	14.1	30.4	$<$10	9.20	0.09	280.5	15.3
Cat Arm	2.5	5.52	15	21.4	17.5	8.65	0.17	455.8	30.3

C = control pond
TOC = total organic carbon
TON = total organic nitrogen

Arm was used to represent background values. The modal fork lengths for ouananiche, brook trout and arctic charr were 30, 20 and 25 cm, respectively. Mean fork lengths for ouananiche, brook trout and arctic charr were similarly 27.0, 18.5, and 19.5 cm, respectively.

Standard length mercury levels in ouananiche ranged from 0.23 (Cochrane Pond) to 0.86 (Long Pond) ppm. Ouananiche in excess of the 0.5 ppm Canadian Safety Limit were collected from 14 of 16 sites (including control ponds) while standard mean mercury levels exceed this limit in 8 reservoirs (Table 4). Brook trout standard length mercury levels ranged from 0.13 (Red Indian Lake) to 0.59 (Mount Carmel Pond) ppm and trout above 0.5 ppm were found in 8 of 17 sites, including control ponds. Standard length mean mercury in brook trout exceeded the 0.5 ppm limit in only one reservoir (Mount Carmel Pond). Standard length mercury levels in arctic charr ranged from 0.22 (Trinity Pond) to 0.72 (Cat Arm) ppm with charr above the Canadian Safety Limit found in 3 of 7 sites. Only charr in Cat Arm had a mean standard mercury level exceeding the Canadian Safety Limit. One-way ANOVA indicated a significant difference ($p < 0.05$) between ouananiche and brook trout mean mercury levels but no difference between arctic charr and brook trout or arctic charr and ouananiche.

Fish mercury levels related to reservoir characteristics

Of the 12 physical and chemical variables, age of the reservoir (AGE; $R = -0.745$, $p = 0.013$) and flooded area ($\log_{10}$ AREA FLOODED; $R = 0.674$, $p = 0.032$) were significantly ($p < 0.05$) correlated with the standard length mercury (HG) content of ouananiche. A 2 variable multiple regression model of HG versus AGE and $\log_{10}$ AREA FLOODED, significant (at the $p < 0.05$ level), was as follows:

$$\text{HG} = 0.453 + (0.00357 * \text{AGE}) + (0.0836 * \log_{10} \text{AREA FLOODED}) \quad (R = 0.715,\ p = 0.04) \qquad (1)$$

These results therefore suggest that ouananiche mercury levels were a function of age of the reservoir and size of the area flooded in creating the impoundment.

For brook trout, no significant relationships were determined using Pearson correlation techniques between standard mercury content and any of the 12 physical and chemical characteristics. Plots of the standard mean mercury content with reservoir age and $\log_{10}$ of the flooded area revealed a scattered distribution with no clear trend. Therefore, based on methods employed in this analysis, the results suggest that mercury levels observed in brook trout are not related to any of the physical and chemical reservoir characteristics investigated in this study.

Table 4. Summary statistics of fish mercury levels, regression equations of [Hg] vs fork length [FL] (with *p*-value), number of fish in excess of 0.5 ppm Hg, and 'Standardized' Mean Hg by species and sampling site.

Site	N	*p*-value	Regression equation	Mean Hg (ppm)	Range	S.D.	$N > 0.5$ ppm (%)	Standardized mean Hg (ppm)
Arctic charr								
Trinity Pond	30	0.5106	$Hg = 0.189 + (0.00152\ FL)$	0.215	0.24	0.059	0 (0)	0.215
Cold Spring Pond	10	0.9502	$Hg = 0.356 - (0.00188\ FL)$	0.334	0.14	0.052	0 (0)	0.309
Cat Arm '82	27	0.0004	$Hg = -0.178 + (0.0234\ FL)$	0.153	0.16	0.044	0 (0)	0.407
Cat Arm	114	<0.0001	$Hg = 0.172 + 0.0219\ FL$	0.629	0.88	0.176	87 (76)	0.720
Long Pond	22	0.0361	$Hg = 0.0188 + (0.0175\ FL)$	0.332	0.27	0.067	1 (5)	0.456
Granite Lake	25	0.0999	$Hg = 0.158 + (0.0115\ FL)$	0.383	0.43	0.115	2 (8)	0.446
Meelpaeg Lake	27	<0.0001	$\log_{10} Hg = -1.71 + (0.919 \log_{10} FL)$	0.250	0.31	0.080	0 (0)	0.376
Brook Trout								
Middle Gull Pond (C)	26	0.0001	$\log_{10} Hg = -1.37 + (0.444 \log_{10} FL)$	0.154	0.25	0.066	0 (0)	0.161
Eclipse Pond (C)	20	<0.0001	$\log_{10} Hg = -2.96 + (1.58 \log_{10} FL)$	0.143	0.48	0.130	1 (5)	0.125
Rocky Pond (C)	39	<0.0001	$Hg = 0.132 + (0.000281\ FL^2)$	0.199	0.89	0.140	1(3)	0.244
Cochrane Pond	21	0.9258	$Hg = 0.194 + (0.000298\ FL)$	0.199	0.21	0.059	0 (0)	0.120
Bay Bull's Big Pond	20	0.9613	$Hg = 0.126 + (0.000128\ FL)$	0.128	0.15	0.051	0 (0)	0.129
Mobile First Pond	20	0.8217	$Hg = 0.161 + (0.0000188\ FL^2)$	0.165	0.15	0.045	0 (0)	0.169
Mobile Big Pond	27	0.0001	$Hg = 0.0699 + (0.00813\ FL)$	0.205	0.28	0.064	0 (0)	0.233
Mount Carmel Pond	30	<0.0001	$\log_{10} Hg = -2.39 + (1.66 \log_{10} FL)$	0.627	1.73	0.508	13 (43)	0.589
Sandy Lake	27	0.0005	$Hg = -0.187 + (0.0250\ FL)$	0.334	0.98	0.324	6 (22)	0.313
Hind's Lake	14	0.0242	$Hg = 0.0204 + (0.00604\ FL)$	0.136	0.20	0.052	0 (0)	0.141
Red Indian Lake	17	0.1032	$Hg = 0.0574 + (0.00366\ FL)$	0.115	0.14	0.035	0 (0)	0.131
Joe Dennis Pond	26	<0.0001	$Hg = -0.445 + (0.518 \log_{10} FL)$	0.189	0.030	0.083	0 (0)	0.229

Table 4. Continued.

Site	N	*p*-value	Regression equation	Mean Hg (ppm)	Range	S.D.	$N > 0.5$ ppm (%)	Standardized mean Hg (ppm)
Great Burnt Lake	28	0.0513	$Hg = -0.275 + (0.0288\ FL)$	0.450	0.99	0.286	7 (25)	0.301
Cold Spring Pond	48	<0.0001	$\log_{10}Hg = -3.04 + (1.88 \log_{10}FL)$	0.272	1.51	0.219	3 (6)	0.255
Long Pond	33	0.9762	$Hg = 0.242 - (0.000278\ FL)$	0.164	0.98	0.164	1 (3)	0.236
Cat Arm	58	<0.0001	$\log_{10}Hg = -0.993 + (0.0193\ FL)$	0.260	0.42	0.094	1(2)	0.247
Granite Lake	10	0.0998	$Hg = -0.308 + (0.0299\ FL)$	0.253	0.30	0.110	0 (0)	0.290
Ouananiche								
Middle Gull Pond (C)	26	<0.0001	$Hg = 0.101 + (0.000218\ FL^2)$	0.375	0.64	0.193	6 (23)	0.297
Eclipse Pond (C)	26	<0.0001	$Hg = -0.344 + (0.0220\ FL)$	0.270	0.61	0.168	4 (15)	0.316
Rocky Pond (C)	40	<0.0001	$Hg = -0.257 + (0.0222\ FL)$	0.338	0.86	0.186	7 (18)	0.409
Cochrane Pond	21	0.0290	$\log_{10}Hg = -1.37 + (0.500 \log_{10} FL)$	0.214	0.76	0.157	1 (5)	0.234
Mobile First Pond	21	<0.0001	$Hg = -0.109 + (0.0227\ FL)$	0.401	0.97	0.309	6 (29)	0.572
Mobile Big Pond	23	<0.0001	$Hg = -0.185 + (0.0212\ FL)$	0.284	0.97	0.261	5 (22)	0.451
Mount Carmel Pond	14	<0.0001	$\log_{10}Hg = -1.22 + (0.0334\ FL)$	0.304	1.31	0.321	1 (7)	0.605
Trinity Pond	17	0.0603	$Hg = 0.148 + (0.00465\ FL)$	0.300	0.25	0.073	0 (0)	0.288
Sandy Lake	22	<0.0001	$Hg = -1.08 + (1.09 \log_{10}FL)$	0.428	0.99	0.306	9 (41)	0.530
Hind's Lake	31	<0.0001	$Hg = -0.158 + (0.0163\ FL)$	0.202	0.52	0.115	1 (3)	0.331
Red Indian Lake	18	<0.0001	$Hg = -0.0164 + (0.00869\ FL)$	0.166	0.43	0.101	0 (0)	0.244
Great Burnt Lake	26	<0.0001	$Hg = -5.60 + (4.32 \log_{10}FL)$	0.891	2.93	0.748	15 (58)	0.781
Cold Spring Pond	31	<0.0001	$\log_{10}Hg = -2.59 + (1.67 \log_{10}FL)$	0.605	1.94	0.480	12 (39)	0.753
Long Pond	83	<0.0001	$Hg = -4.40 + (3.56 \log_{10}FL)$	0.729	2.01	0.395	55 (66)	0.859
Granite Lake	36	0.0008	$Hg = -0.270 + (0.0308\ FL)$	0.595	1.89	0.392	19 (53)	0.654
Meelpaeg Lake	34	0.0535	$Hg = 0.185 + (0.0168\ FL)$	0.757	1.22	0.318	25 (74)	0.689

C = control pond

For arctic charr, data from the six reservoirs and pre-impoundment data for Cat Arm indicated significant correlation with only one parameter; pH ($R = -0.828$, $p = 0.42$).

Discussion

Previous studies of mercury in fish in hydroelectric reservoirs in Newfoundland (Scruton et al. 1994) had focused on analysis of the temporal evolution in mercury levels especially time to return to pre-impoundment levels. That analysis, based on recently created (<12 years) reservoir systems, suggested return times of 10 to 12 years for ouananiche and 7 years for brook trout. Recent re-analyses of this data, with additional monitoring data, suggested return times were under estimated and trends in declining mercury levels were slowing (Scruton et al. 1997). Other global studies have shown a wide range in return times. Abernathy & Cumbie (1977) have indicated return times of from 3 to 5 years in North Carolina reservoirs. In the James Bay development (Quebec), return times in the order of 20 years for the non-piscivorous lake whitefish and 30 years for the piscivorous northern pike were suggested (Brouard et al. 1990). This is similar to findings in Finnish (Verta et al. 1986; Verta 1990), northern Manitoba (Bodaly et al. 1997), and Labrador (Anderson & Scruton 1997) reservoirs.

Research has demonstrated that there are a variety of factors, in addition to age of a reservoir, that can influence the rate of mercury bioaccumulation and subsequent return to background levels. These include features of the terrestrial flooded area (areal extent of the flood zone, soil type and geochemistry, organic [DOC] content) (e.g., Bishop et al. 1995), the modifying effects of productivity and chemical characteristics (e.g., pH) of the impoundment (e.g., Akagi et al. 1979; Ramal et al. 1985; Gilmour & Henry 1991), operating characteristics of the reservoir (drawdown, turn over rate, temperature regime) (e.g., Verta et al. 1986), and trophic status and longevity of the fish species in the reservoir (e.g., Brouard et al. 1990). Additionally, there is increasing evidence of atmospheric deposition as an importance source of mercury in the aquatic environment (e.g., Slemr & Langer 1995).

In this study, mercury was correlated with reservoir age and area for ouananiche and pH for arctic charr but not for brook trout. Several authors have reported relationships between the age of an impoundment and fish mercury levels. For example, Verta et al. (1986) found a highly negative correlation ($R = -0.017$) between pike mercury levels and age of reservoirs in Finland. The finding that ouananiche mercury levels were related to the area flooded is also consistent with other studies. Bodaly et al. (1984) and Jackson (1988) demonstrated a strong relationship between fish Hg levels and extent of flooding. Lakes with a high drainage area to lake volume ratio had higher fish mercury levels in Finland (Verta 1990). As increased mercury in fish relative to impoundment is primarily related to stimulated methyl mercury production due to flooding, the increased methyl mercury production is related the quantity of organic matter flooded. Therefore physical variables such as area flooded and area flooded to volume ratios are considered to provide reasonable estimates of increases in methyl mercury concentrations in the system (Johnston et al. 1991).

Mercury enters aquatic organisms through direct absorption from water and through food, with the latter generally considered the more important pathway for bioaccumulation and biomagnification (Huckabee et al. 1979; Rudd et al. 1983). Thus diet, and more importantly a shift to piscivory, may be important in explaining the difference between species in mercury relationships with reservoir characteristics (Brouard et al. 1990). In Newfoundland, ouananiche have generally been shown to be longer lived, grow larger, and demonstrate a greater tendency for piscivory than either brook trout or arctic charr. Consequently, ouananiche would have longer exposure times for bioaccumulation and would also demonstrate greater biomagnification through the food chain. This may, in part, explain the stronger relationships between reservoir age and area flooded with standardized mean mercury levels in ouananiche.

Johnston et al. (1991) demonstrated variability in fish mercury concentrations related to both within lake effects (e.g., change in surface level, percent area flooded, flooded area to lake volume ratio) and effects from upstream reaches (e.g., upstream flooded area, upstream flooded area to lake volume ratio). They determined that changes in upstream areas (and reservoirs) can be as important as changes in the reservoir itself. This is an important observation as several of the reservoirs included in this study are located in the B'aie d'Espoir and Upper Salmon developments and are contained in a sequence of adjacent reservoirs (Granite Lake, Meelpaeg Lake, Great Burnt Lake, Cold Spring Pond and then Long Pond). This would suggest possible contributions of mercury in water in a downstream direction which would further complicate interpretation. Further, the Long Pond reservoir is the last of this series of 5 reservoirs and has been subject to two periods of flooding, including the recent raising of the full supply level in 1992. There is a trend of increasing standard mean mercury in ouananiche through this series of reservoirs with the standard mean mercury content highest at all study sites in Long Pond (Table 4).

Due to bioaccumulation, significant relationships between mercury concentrations and fish age, length, and weight are common (e.g., Bodaly et al. 1984; Jones et al. 1986). It has been a common practice to attempt to correct for this bioaccumulation effect through calculation of standardized mean concentrations (e.g., Brouard et al. 1990). Several authors have demonstrated that slope of the fish mercury versus length relationships are steepest for piscivorous species (e.g., Verta et al. 1986; Brouard et al. 1990). Further, in Newfoundland, salmonids are primarily non-piscivorous in juvenile stages and as smaller adults and only shift to piscivory as larger, older adults. Therefore the fish mercury versus length relationship could include both non-piscivorous and piscivorous fishes in the same population. As standard length analysis assumes similar slopes in the mercury and fish length relationships, this is a possible source of error in this approach to analysis.

A noteworthy finding of this study is the demonstration of fish mercury levels above the Canadian Safety Limit of 0.5 ppm in older impoundments and in the control lakes. This phenomenon has been demonstrated in other regions in North America (e.g., Ontario, McMurty et al. 1989; Quebec, Brouard et al. 1990; Michigan, Grieb et al. 1990) where a large number of natural lakes have reported elevated mercury levels in fish. Previous concern for elevated mercury in fish in Newfoundland had only been in relation to hydroelectric development (Scruton et al. 1994) and this had led to health risk advisories and posting of consumption limits for some reservoirs. Evidence of elevated mercury levels in fish in natural lakes warrants further investigation to determine the source of mercury in natural lakes; determine hydrological, geochemical, and biological processes controlling mercury accumulation; and to establish whether recreational exploitation of fish in these lakes constitutes a human health risk.

The biotic and abiotic mechanisms contributing to formation of methyl mercury after creation of an impoundment and subsequent transfer to the aquatic food chain are complex. The variety of factors influencing fish mercury levels has resulted in considerable effort to develop mechanistic and/or bioenergetic models to predict fish mercury levels in impoundments. Other approaches have attempted to develop more generally predictive relationships to understand fish mercury evolution in reservoirs based largely on physical characteristics (Johnston et al. 1991). These simpler models have been somewhat effective in predicting fish mercury in regions from which they were developed, however they have not been as useful in broader geographical application (Johnston et al. 1991).

We have attempted to use a retrospective analysis, studying a number of systems of various age and size, to explore physical and chemical reservoir characteristics and fish mercury evolution in Newfoundland reservoirs. This analysis has been partially successful in identifying a relationship between mercury and reservoir age and size of flooded area for ouananiche, however it is not possible, at present, to develop generally predictive models for all species found in Newfoundland impoundments. More research is necessary to determine factors affecting fish mercury levels in natural, un-impounded lakes, in order to select suitable control sites and understand geochemical and atmospheric contributions of mercury to the aquatic environment. Continued monitoring of recent hydroelectric developments until background levels are achieved will be important to establish the return times for Newfoundland species under regional conditions.

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