HENV 610

Historical Patterns of Fish Mercury in Four Lakes in the Canadian Boreal

Whitney Light
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Introduction

Fish consumption is the most common path of mercury exposure in humans. The body absorbs almost all of the mercury present in fish muscle tissue (Kerper et al., 1992). The neurotoxic effects of mercury are well known (Mahaffey, 1999). Consequently, fish mercury levels are monitored in commercial fisheries and in many lakes frequented by recreational anglers. In Canada, the issue of fish mercury also affects many indigenous populations who rely on local freshwater fisheries for income as well as food.

As a consequence of resource development, including mining and hydroelectric projects, many lakes in North America have been impacted by increased levels of mercury available for bioaccumulation in fish. For example, in riverine systems, flooding may create conditions that give rise to Hg(II)-methylating bacteria that turn mercury into methylmercury that enters the food stream (Green et al., 2016). In other instances, atmospheric deposition of mercury has occurred due to gold mining and coal combustion, among other activities (Hrabik and Watras, 2002).

The consequences of increased mercury in the environment are not temporary. In the case of reservoirs created by hydroelectric development it has been shown to take 20 years or more for mercury levels to return to baseline levels (Rosenberg et al., 1997). However, other studies have reported short-term (less than a decade) responses to declines in mercury deposition (Hrabik and Watras). Reported patterns of temporal change run the gamut of increases and decreases, apparently dependent on local dynamics that may or may not support mercury methylation (Eagles-Smith et al., 2016).

This project investigates the issue of fish mercury over time in four lakes in the boreal region of the prairie provinces: Cumberland Lake, SK; Southern Indian Lake, MB; Lake Athabasca, SK/AB; and Primrose Lake, SK. The choice of lakes was made to balance a coherent geographic theme with data availability and a variety of lake histories. Cumberland Lake and Southern Indian Lake are influenced by provincial hydro-electricity systems. Lake Athabasca is synonymous with Cold War-era uranium mining. Primrose Lake is contained within the Cold Lake Air Weapons Range.

For these lakes, the project inquired into change in fish mercury levels over time, as well as magnitude and direction of change between the years for which data was available, 1974 to 2006. The hypothesis was that mercury levels would have attenuated over time, since major resource development occurred in the 1960s and 1970s. If there was a decline, did it signal a return to food-safe levels? Currently, Health Canada guidelines state that 0.5 ppm is the upper limit of mercury in fish muscle tolerable for most retail fish. However, there is no known safe level of exposure (Bose-O'Reilly, 2011), and the limit for subsistence consumption of fish is often cited as 0.2 ppm (Lockhart et al., 2005). Where possible, fish species from different trophic levels were included in regression analysis. However, most of the data centered on yellow pickerel (*Stizostedian vitreum*), which was used to more robustly test the hypothesis of change over time. Other species included were northern pike (*Esox lucius*), goldeye (*Hiodon alosoides*), and lake whitefish (*Coregonus clupeaformis*). The project also aimed to detect species differences in mercury levels within lakes, in order to test the idea that it may be advisable to eat some fish species more than others. An attempt was made to test if yellow pickerel mercury levels between the four lakes differed significantly.

Data description

The sample data came from the Contaminants in Fish Database, which is publicly accessible online through the Government of Canada's Open Government portal and contains over 198,000 measurements of various contaminants, primarily mercury, in fish caught between 1970 to 2006 in lakes and rivers across the country. The testing was conducted in the Winnipeg laboratory of the Fish Inspection Branch of Fisheries and Oceans Canada and by the Canadian Food Inspection Agency to determine market access for fish products and to ensure food safety according to Canadian guidelines (Freshwater Institute correspondence, Nov. 19, 2020). The fish were caught either by experimental netting or taken out of commercial fishing hauls. Typically, a piece of dorsal muscle tissue, or sometimes liver tissue, would be sealed in a plastic bag, frozen and shipped to Winnipeg for analysis (Lockhart et. al., 2005). The lab was closed in 2006.

The complete database consists of seven separate comma-separated value (CSV) files, which for this project were compiled into one master file with each record consisting of a sample date, analysis date, lab identifier, lake (or river) name, geographic coordinates, species name, weight measurement, length measurement, organ tissue identifier, contaminant identifier, and contaminant measure in parts per million. Columns and variable coding were consistent across the datasets, making it straightforward to bind the datasets together. Only a small number of records had to be recoded to standardize the sample date variable. For the purposes of this project, the variables of interest were sample date, species name, fish length, and contaminant measure. Only measures of mercury in muscle tissue were included in the subset.

Methods

Statistical tests were carried out at the $\alpha = 0.05$ level using R version 4.0.0 (R Core Team, Vienna, Austria, 2020).

In order to assess sample date as a predictor of mercury levels and generate a hypothesis about fish mercury in the selected lakes over time, the project employed multiple linear regression. Following previous studies, length was posited to be a probable important predictor of mercury, as was fish species (Wente, 2004), which was included as a factor variable. A separate regression for each lake was conducted, so as not to conflate fish differences influenced by geographic and geomorphic lake characteristics with size, sample date, and species effects.

The assumptions of multiple linear regression are that a linear relationship exists between the predictors and the dependent variable, that the predictor variables are not highly correlated with each other, and that the predictors are known without error. Furthermore, it is assumed that the residuals will be independent, identically normally distributed random variables, which can be confirmed by a statistical test of residuals (e.g. Shapiro-Wilks test of normality) and diagnostic plots of residuals, which can also reveal unequal variance if it exists. In addition, the data should be checked for outliers and high leverage points that could influence the model; such points are evident in model diagnostic plots of Cook's distance.

Fish mercury levels did not follow a normal distribution. Date sets for each lake were right skewed and thus required transformation to meet the criteria for regression. The R package "bestNormalize," which runs a battery of normalization techniques and reports the ideal transformation, helped solve this problem. In some cases, a simple log transform worked; in others, the Yeo-Johnson or ordered quantile technique performed better.

Next, a linear model was fit using R software of the following form:

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lm(transformed mercury ~ sample date + species + length)
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Alternative models excluding sample date were also fit for comparison purposes. The Akaike Information Criterion (AIC) was used to compare models and it was found that models excluding sample date were not significantly different (an AIC difference of 2 or more is considered significant) from models including them, and the latter had the lowest AIC as well as slightly higher values of adjusted R-squared.

The regression supported a hypothesis that fish mercury is declining over time in some lakes. To further investigate, analysis of variance (ANOVA) was conducted on sample date grouped into three equal-interval bins with the aim of comparing mean mercury levels among the date bins. Effort was made to standardize for fish length and species. Since more data was available for pickerel, only samples of pickerel of length 350 mm to 550 mm (a common catch size in all lakes) were included in the ANOVAs. The ANOVA technique assumes that data is normally distributed within each group, and that variance is equal among groups. Shapiro and Levene tests were used to test these assumptions, and in most cases, using appropriately transformed mercury levels permitted the assumptions of ANOVA to be met. Significant results were followed up with a Tukey Honest Significant Differences test. Where the assumptions were not met, the non-parametric Kruskal-Wallis test, which more generally evaluates whether samples come from the same distribution, was tried and followed up with a pairwise Wilcox rank sum test if appropriate.

An ANOVA approach was also used to examine species difference in mercury concentration in two lakes where data for three species including different trophic levels was available. Within a limited date interval, specimens of each species were deemed "small" or "large," in order for small specimens to be compared with small of other species, and large with large. Species groups were checked for normality and equal variance and an ANOVA or Kruskal-Wallis was conducted as appropriate.

Results

Lake Athabasca

The Lake Athabasca data set contained samples across the complete time period for pickerel, pike, and goldeye, which were included in a regression analysis. As the descriptive statistics in Table 1 show, the mean and median mercury for all species in this sample was slightly above half the Canadian limit for retail fish of 0.5 ppm. However, higher maximum levels and median absolute deviations were observed in northern pike.

With Yeo-Johnson transformation conditions of normality and equal variance of residuals were met upon inspection of diagnostic plots and a Shapiro test of residuals ($p = 0.0781$). As seen in Table 2, sample date appeared not to be a significant predictor of mercury in this case, while as expected fish length appeared strongly significant. The results also suggest a significant difference in the regression lines for goldeye (base factor) and northern pike. The adjusted R-squared is low at 0.117, however the overall F of the regression was strongly significant.

The regression is plotted in for sample date in Figure 1 and for length in Figure 2. The former illustrates the indeterminacy of the effect of sample date, while the latter illustrates how species separate by length with a corresponding effect on expected mercury levels. The intercepts for goldeye and pike are clearly different, but the rate of mercury rise with growth appears similar.

Table 1: Lake Athabasca Descriptive Statistics

Measure	Species	n	Mean	Std. Dev.	Median	MAD	Min.	Max.
Hg (ppm)	Goldeye	60	0.27	0.1	0.26	0.1	0.11	0.59
	Yellow Pickerel	150	0.29	0.11	0.28	0.09	0.05	0.81
	Northern Pike	49	0.3	0.16	0.28	0.16	0.04	0.87
Length (mm)	Goldeye	60	336.9	34.88	343	28.17	265	410
	Yellow Pickerel	150	373.5	59.83	355.5	37.81	290	555
	Northern Pike	49	547.45	107.07	520	81.54	435	880

Table 2: Results of regression analysis for Lake Athabasca

	Dependent variable:
	Yeo-Johnson Hg
Sample Date	-0.00001
	(0.00002)
Species (Pickerel)	-0.045
	(0.149)
Species (Pike)	-1.024^{***}
	(0.268)
Length (mm)	0.005^{***}
	(0.001)

Constant	-1.829***
	(0.340)
Observations	259
R^2	0.131
Adjusted R^2	0.117
Residual Std. Error	0.940 (df = 254)
F Statistic	9.551*** (df = 4; 254)
Note:	*p<0.05, **p<0.01, ***p<0.001

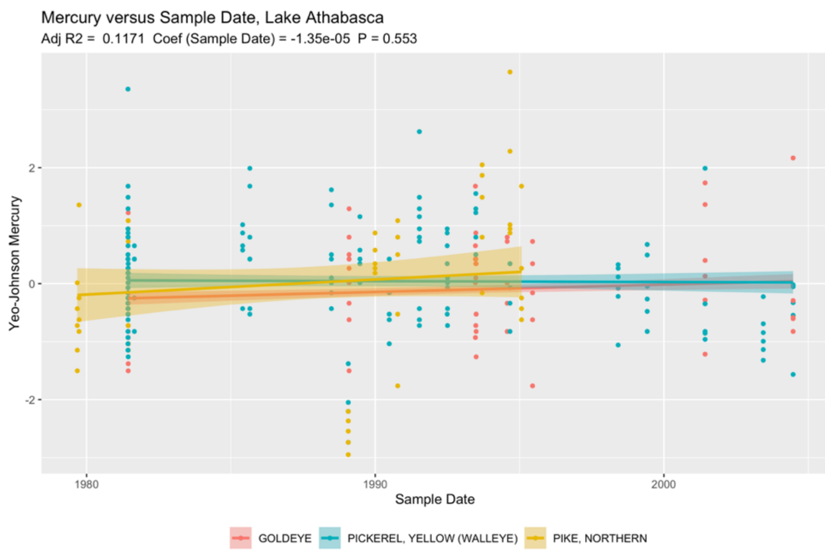

Fig. 1. The Lake Athabasca regression produced a non-significant correlation between sample date and mercury concentration. The lines for goldeye and pickerel are close to horizontal while pike (yellow) mercury concentration appears to increase over time.

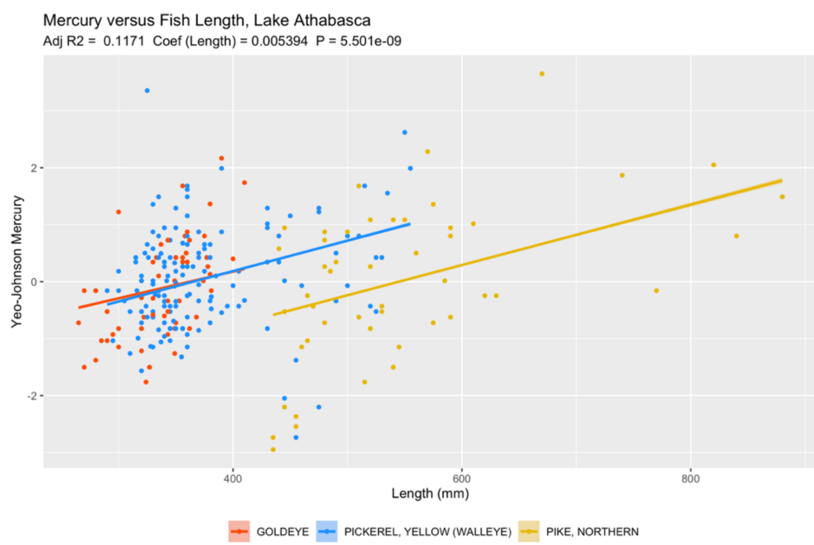

Fig. 2. The Lake Athabasca regression produced a significant correlation between fish length (mm) and mercury concentration. The regression lines for goldeye (red) and pike (yellow) differ significantly.

Because goldeye and northern pike samples were not well represented across the range of sampling dates, a second regression for yellow pickerel only was conducted, the results of which appear in Table 3. This regression found a significant coefficient for sample date (-0.0001, p = 0.0288), indicating that mercury levels in pickerel have gone down since the start of sample collection.

Table 3: Results of pickerel regression, Lake Athabasca

	Dependent variable:
	ORQ Transformed Hg
Sample Date	-0.0001^{**}
	(0.00003)
Length (mm)	0.004^{***}
	(0.001)
Constant	-0.859
	(0.528)
Observations	150
R^2	0.074
Adjusted R^2	0.062
Residual Std. Error	0.967 (df = 147)
F Statistic	5.895^{***} (df = 2; 147)
Note:	$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

In order to understand what this means in practice, I looked at the model's predictions for a common catch-size pickerel (length 400 mm) in 1975 and 1995. In 1975, the mean mercury would be 0.33 ppm, with prediction interval 0.16 ppm to 0.70 ppm. In 1995, mercury would be 0.27 ppm, with prediction interval 0.10 ppm to 0.52 ppm. The interval is wide, however, it appears mercury levels came down by close to 20% to be mostly within the legal limit.

Sample Date ANOVA

The pickerel sample was binned into three date ranges with the intent to conduct an ANOVA. However, the assumption of normality was violated in one date bin, and the equal variance assumption was violated, rendering both ANOVA and Kruskal Wallis tests invalid.

Species ANOVA

Lake Athabasca samples from 1985 to 1995 (when most samples were collected) were categorized as either small or large specimens for each species. Based on histograms, small pickerel and goldeye were less than or equal to 350 mm; small pike were less than 450 mm. Levene and Shapiro-Wilk tests for equal variance and normality were satisfied before conducting an ANOVA on small fish, which found significant difference among species (p = 0.00165 with 42 degrees of freedom). A follow up Tukey HSD showed the differences were between pike and goldeye (p = 0.0156) and between pike and pickerel (p = 0.001). The sample mean for pike was 0.13 ppm, 0.26 ppm for goldeye, and 0.30 ppm for pickerel.

Similarly, based on histograms, pickerel longer than 450 mm were deemed large, while large goldeye and pike were those longer than 350 mm and 600 mm, respectively. Again, equal variance and normality tests were met. The ANOVA did not find significant differences between large specimens of the species (p = 0.105).

Primrose Lake

Yellow pickerel and northern pike samples were analysed. Mercury levels in the sample appeared similar for both species, as shown in Table 4. Both the mean and median mercury levels were within the 0.2 ppm subsistence limit, with maximum observations only slightly over the retail limit.

Table 4: Primrose Lake Descriptive Statistics

Measure	Species	n	Mean	Std. Dev.	Median	MAD	Min.	Max.
Hg (ppm)	Yellow Pickerel	70	0.19	0.08	0.17	0.06	0.08	0.52
	Northern Pike	45	0.2	0.1	0.17	0.07	0.06	0.57
Length (mm)	Yellow Pickerel	70	509.86	46.53	510	44.48	370	600
	Northern Pike	45	567.44	95.51	600	88.96	340	740

The Yeo-Johnson technique was used to normalize mercury levels for regression. As recorded in Table 5, sample date was not a significant predictor of mercury level. The intercept did not different significantly between species, but log length was a strong predictor. Figure 3 illustrates the uncertainty in sample date as a predictor of mercury. There is the suggestion of a downward trend in northern pike, however, this may be an artifact of the small sample size. According to this model, the mean mercury level for a common catch-size yellow pickerel (400 mm) in 1975 would be 0.15 ppm, with prediction interval 0.06 ppm to 0.33 ppm. For 1995, the mean would be 0.13 ppm, with prediction interval 0.05 ppm to 0.27 ppm.

Sample Date ANOVA

The yellow pickerel samples were binned into three equal-interval date ranges. Using Yeo-Johnson transformed mercury, assumptions of normality within each date bin and equal variance were met. The ANOVA resulted in a non-significant difference between date bins (p = 0.655), confirming that mercury levels in pickerel have remained stable over time at Primrose Lake. The mean for the early period was 0.17 ppm, 0.17 for the middle period, and 0.16 for the late period, all well under the 0.5 ppm retail limit and suitable even for subsistence.

Table 5: Regression results for Primrose Lake

	Dependent variable:
	Yeo-Johnson Hg
Log Length	6.869***
	(1.500)
Species (Pike)	-0.296
	(0.192)
Sample Date	-0.0001
	(0.00004)
Constant	-18.127***
	(4.066)
Observations	115
R^2	0.173
Adjusted R^2	0.151
Residual Std. Error	0.922 (df = 111)
F Statistic	7.743*** (df = 3; 111)
Note:	*p<0.05, **p<0.01, ***p<0.001

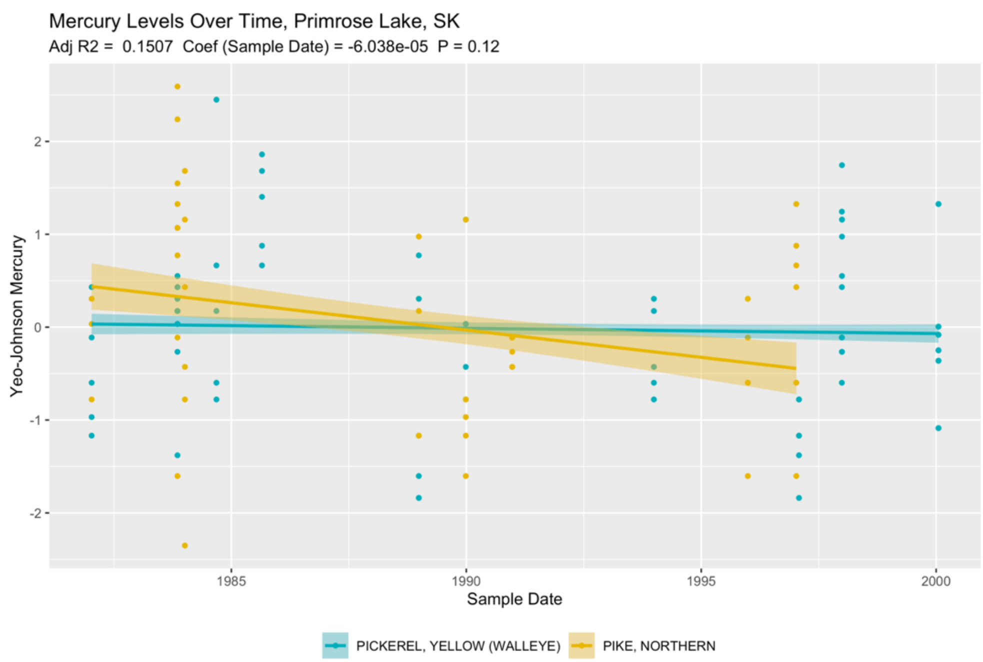

Fig. 3. The regression resulted in a non-signficant negative coefficient for sample date, suggesting mercury levels have remained stable over time at Primrose Lake.

Southern Indian Lake

Samples of lake whitefish, northern pike, and yellow pickerel were analysed. Table 6 shows that the mean and median levels of mercury in yellow pickerel and northern pike met or exceeded the 0.5 ppm retail limit, with maximum observations above the 1.0 ppm limit reserved for certain ocean species such as swordfish. Lake whitefish appeared to have much lower levels of mercury mostly well below the 0.5 ppm limit.

The ordered quantile technique was used to normalize the mercury levels for regression, and a complete model was fit using sample date, species and length as predictors. The sample was too large to run a Shapiro test on residuals, but diagnostic plots confirmed equal variance and normality. As recorded in Table 7, all coefficients in this case were significantly non-zero, showing mercury levels decreasing modestly over time.

Table 6: Southern Indian Lake Descriptive Statistics

Measure	**Species**	**n**	**Mean**	**Std. Dev.**	**Median**	**MAD**	**Min.**	**Max.**
Hg (ppm)	Yellow Pickerel	1360	0.58	0.32	0.5	0.21	0.02	2.88
	Northern Pike	2149	0.76	0.34	0.7	0.25	0	3.05
	Lake Whitefish	1777	0.13	0.1	0.1	0.06	0.01	0.71
Length (mm)	Yellow Pickerel	1360	380.57	52.77	380	59.3	180	560
	Northern Pike	2149	572.29	108.69	554	97.85	280	1030
	Lake Whitefish	1777	373.77	55.03	380	51.89	166	560

Table 7: Regression results for Southern Indian Lake

	Dependent variable:
	ORQ Transformed Hg
Sample Date	-0.00003^{***}
	(0.00001)
Species (Pike)	-0.117^{***}
	(0.029)
Species (Whitefish)	-1.287^{***}
	(0.022)
Length (mm)	0.003^{***}
	(0.0001)
Constant	-0.674^{***}
	(0.049)
Observations	5,286
R^2	0.638
Adjusted R^2	0.638
Residual Std. Error	0.601 (df = 5281)
F Statistic	$2{,}330.526^{***}$ (df = 4; 5281)
Note:	$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

However, as Figure 4 illustrates, testing occurred mainly in the 1980s, with few observations made past 1989. Yet the adjusted R-squared of 0.638 is notably higher than R-squared values reported for other models in the study, likely owing to the much larger sample size.

Figure 5 shows the association between length and mercury level, as well as the clearly lower levels of mercury in lake whitefish, likely attributable to its lower trophic level. According to this model, the mean mercury level of a 400 mm pickerel in 1975 would be 0.62 ppm, with 95% prediction interval 0.13 ppm to 1.16 ppm. For 1995, the mean is 0.53 ppm, prediction interval 0.09 ppm to 1.02 ppm.

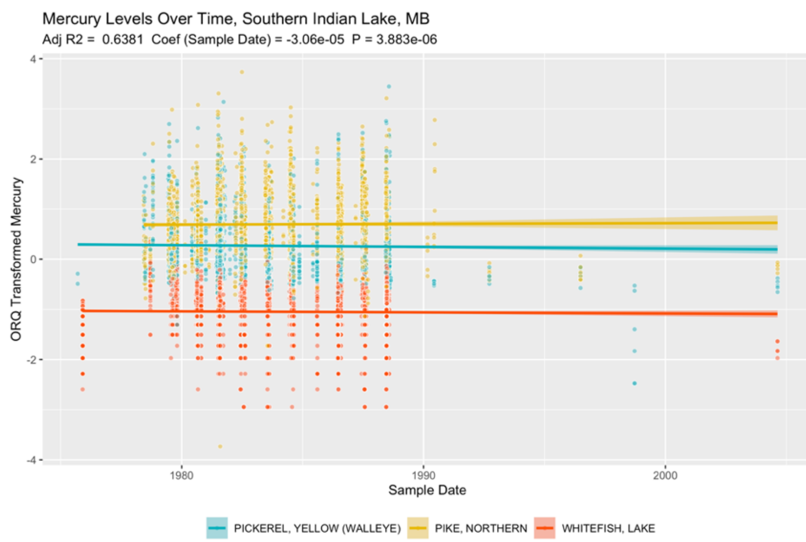

Fig. 4. The regression resulted in a significantly negative coefficient for sample date, however the plot also shows that few samples were recorded past 1989.

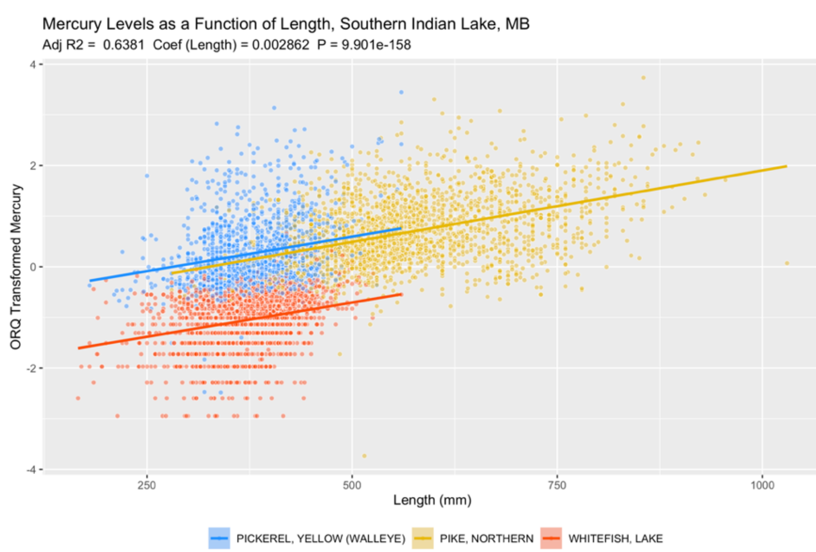

Fig. 5. The regression resulted in a significantly positive coefficient for length. Intercepts for the three species also differed significantly, with clearly lower mercury levels recorded in lake whitefish.

Sample date ANOVA

The yellow pickerel samples were binned into three equal-interval date ranges with the intent to conduct an ANOVA on mercury across date bins. The normality assumption was not met, however, the equal variance assumption was, according to Levene's test ($p = 0.1046$). Therefore, a Kruskal-Wallis test was conducted, with the null hypothesis that the mercury samples in each date bin come from the same distribution. The test found a significant difference among groups ($p = 2.479e-06$), which was followed up with a pairwise Wilcox rank sum test. Significant differences ($p < 0.01$) existed between all pairs. The Kruskal-Wallis test does not explicitly test differences in means. Medians were 0.54 ppm, 0.45 ppm, and 0.30 ppm, for the early, mid, and late period, respectively.

Species comparison ANOVA

Samples of big and small fish from the years 1980-1985 were subset in order to compare mercury concentration distributions among species. Among small fish ($n = 476$), the equal variance assumption was met (Levene's test, $p = 0.401$), however, normality among groups was not. Small was defined as less than or equal to 300 mm for whitefish, 450 mm for pike, and 350 mm for pickerel. A Kruskal-Wallis test was conducted, which found significant group differences. A pairwise Wilcox test showed the differences to be between pike and whitefish ($p < 2e-16$) and pickerel and whitefish ($p < 2e-16$), but not between pike and pickerel. Median mercury in whitefish was 0.08 ppm, while medians for pickerel and pike were 0.49 ppm and 0.54 ppm, respectively. A similar test was attempted for large fish, however equal variance and normality assumptions could not be met. However, a boxplot of large fish showed the same pattern, with highest concentrations observed in pike, as in Figure 6.

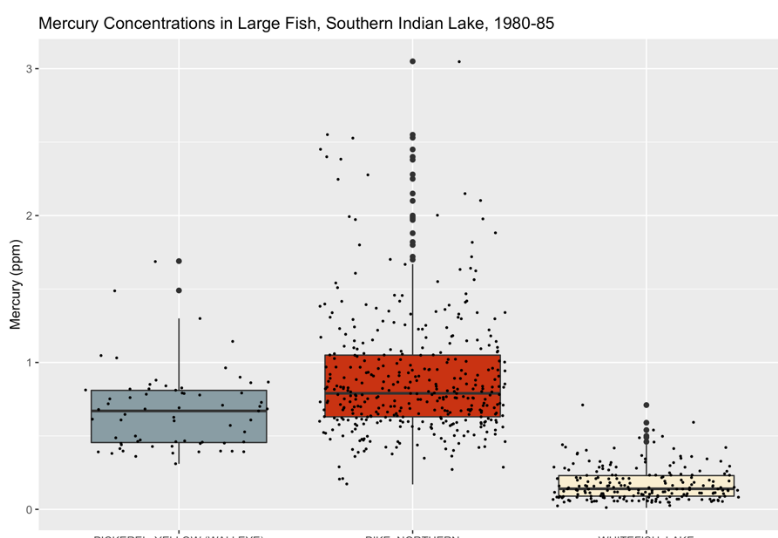

Fig. 6. Pickerel larger or equal to 450 mm were deemed large, as were pike 600 mm and larger, and whitefish 400 mm and larger. Lake whitefish show conspicuously lower mercury concentrations, and the highest concentrations were observed in pike.

Cumberland Lake

Yellow pickerel and northern pike samples were analysed. As Table 8 shows, mean and median mercury levels for both species in this sample hovered around the retail limit of 0.5 ppm, with much higher maximum levels recorded.

Mercury levels were log transformed and a regression of sample date, species and length onto mercury was conducted. Diagnostic plots of residuals appeared to satisfy the equal variance criteria, and a Shapiro test for normality confirmed normally distributed residuals (p = 0.1123). As shown in Table 9, the model indicated significantly non-zero coefficients for all predictors, with sample date having a negative effect on mercury, which is illustrated in Figure 7.

According to this model, a 400 mm pickerel in 1975 would have mean mercury 0.49 ppm, with 95% prediction interval 0.15 ppm to 1.60 ppm. In 1995, the mean would be 0.29 ppm, prediction interval 0.09 ppm to 0.95 ppm.

Table 8: Cumberland Lake Descriptive Statistics

	Species	n	Mean	Std. Dev.	Median	MAD	Min.	Max.
Hg (ppm)	Yellow Pickerel	355	0.61	0.43	0.5	0.33	0.13	2.93
	Northern Pike	184	0.53	0.36	0.42	0.24	0.05	2.03
Length (mm)	Yellow Pickerel	355	438.92	54.94	445	44.48	295	762
	Northern Pike	184	527.02	120.57	505	111.19	130	977

Table 9: Regression results for Cumberland Lake

	Dependent variable:
	Log Hg
Sample Date	-0.0001^{***}
	(0.00002)
Species (Pike)	-0.317^{***}
	(0.061)
Length (mm)	0.002^{***}
	(0.0003)
Constant	-1.491^{***}
	(0.148)
Observations	539
R^2	0.144
Adjusted R^2	0.139
Residual Std. Error	0.597 (df = 535)
F Statistic	29.921^{***} (df = 3; 535)
Note:	$^{*}p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$

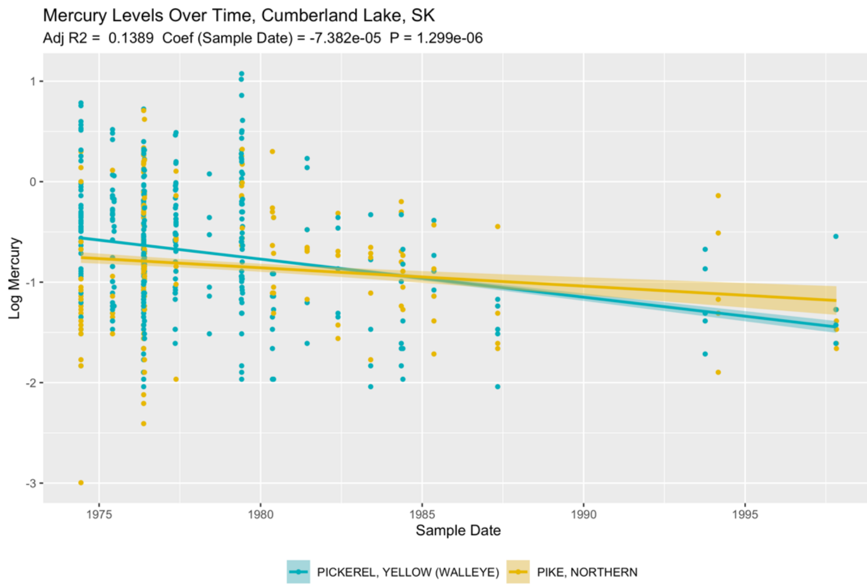

Fig. 7. The regression resulted in significantly negative coefficient for sample date, indicating mercury levels have decreased over time. However, the plot also shows the increasing uncertainty in the mean for later years, due to fewer recorded samples.

Sample date ANOVA

Yellow pickerel samples were binned into three equal date ranges. Assumptions of normality within groups and equal variance were met using log transformed mercury values. The ANOVA found a significant difference among date bins (p = 8.27e-06), and it was followed with a posthoc Tukey test to locate differences. The early period differed significantly from the middle and late periods, however, no difference was detected between middle and late periods, suggesting that mercury levels stabilized in a later years. Mean mercury for the early period was 0.66 ppm, while middle and late periods had mean levels of 0.37 ppm and 0.33 ppm, respectively.

Discussion

Lake Athabasca

Of the entire sample, 95% of specimens fell within the Health Canada limit of 0.5 ppm; only 23% fell within the 0.2 ppm subsistence limit. For all species, sample date appeared to have a negligible effect on mercury concentration, although there was some indication of decline in pickerel. The results accord with the lake's history as a site of gold mining in the 1930s and 1940s, and of uranium mining between 1955 and 1963 (the Gunnar open pit mine); runoff from tailings ponds was a source of heavy metal contamination and remedial work has been ongoing (Waite, 1988). The process of mercury attenuation therefore may have started before data collection began. Moreover, the vast size of the lake may help dilute concentrations.

Nonetheless, the level of fish mercury is far from zero. Analysis of variance suggested that small goldeye and pickerel contain half the retail limit of mercury and twice the concentration of small pike, while the difference between species recedes for large specimens. This makes sense considering that fish tend to grow slower in cold lakes at high latitudes (Hartman, 2009). Fish age may be as important as length. Given that Lake Athabasca is regarded as a prime angling destination, and that contaminants may be increasing again due to oilsands development (Kelly et al., 2010), mercury concentrations should be carefully monitored.

Primrose Lake

Primrose Lake falls within the Cold Lake Air Weapons Range and was used to launch sounding rockets through the 1970s and existed in proximity to other activities of the Department of National Defense. However, the natural environment appears to have been preserved in relatively pristine condition, and efforts were made in 2000 by the Government of Saskatchewan to designate the lake and surrounds an ecological reserve (Saskatchewan Environment and Resource Management). A small commercial fishery is currently operated there.

According to the findings, the weapons range activities appear not to have impacted fish mercury. Concentrations were low compared to the other lakes under review and remained so over time. Continued monitoring and site preservation could provide useful data about expected baseline mercury concentrations in mid-boreal uplands.

Southern Indian Lake

In 1976, Southern Indian Lake was flooded 3 m above average lake level, expanding its footprint by 21%, as part of the Churchill River Diversion project to develop hydroelectricity in northern Manitoba. The lake became an important case study in the role of impoundment on increased lake mercury in an environment mostly unaffected by industrial pollution (Bodaly et al., 1984). An important freshwater fishery run by the O-Pipon-Na-Piwin Cree Nation was effectively destroyed, and the community, which I visited in August 2018 with researchers from the University of Manitoba, has yet to recover from the trauma.

Therefore, results showing elevated fish mercury were not surprising. However, when Bodaly et al. conducted their study, they noted that fish length seemed not to correlate with mercury concentration, pre- or post-impoundment, except in pike. This is in contrast to the current findings, which showed correlation between length and mercury across species. It may be attributed to the larger size and timespan of the data set.

Finally, the indication of declining mercury over time is hopeful, particularly for lake whitefish, which show much lower levels than pike and pickerel of any size. It is possible that lake whitefish are suitable for subsistence consumption. Future studies could analyse the potential for a small indigenous fishery to be recovered.

Cumberland Lake

Cumberland Lake is the largest lake of the Saskatchewan River Delta wetland and located downstream of the E.B. Campbell hydroelectric dam, which was constructed in 1963. The literature suggests that mercury effects of such projects are confined to the reservoir itself and up to 100 km downstream (Rosenberg et al.). Cumberland Lake is at the upper limit of that distance, yet its lake sturgeon fishery was closed between 1970 and 1973 due to elevated mercury (Green et al.).

The findings accord with this history, with the 1974-1985 period showing substantially higher mean mercury (above 0.5 ppm) than later periods recorded in the sample. The lake appears not to have been studied as thoroughly as Southern Indian Lake, although elevated blood mercury has been recorded in the indigenous community of Cumberland House, and mercury monitoring by researchers at the University of Saskatchewan continues. That mercury appeared to be decreasing significantly over time aligns with more recent research by Green et al., who compared historical Government of Saskatchewan data with contemporary samples. They found that by 2016, mercury levels for pike and pickerel were within Health Canada guidelines for retail fish.

Study limitations

Inconsistency of sampling over time, among species, and among lakes made analysis of mercury change over time challenging, and comparison of lakes nearly impossible due to extreme disparities in variance. It also prevented thorough species comparison. Somewhat arbitrary choices had to be made in order to compare species of different size at date intervals that happened to contain samples. A more thorough data set would have permitted consistent subsetting for comparison purposes. Furthermore, the limited predictive power of regression models may be due to lack of fish age information in addition to small sample sizes.

Conclusion

The project results confirmed long time frames of 20 years and more for mercury levels to attenuate after elevation by human disturbances. By 1995-2006, mercury levels in pickerel were unsuitable for subsistence in three of four lakes, with the exception of Primrose Lake, which did not experience large-scale disturbance.

The project found mixed results on the question of whether fish at lower trophic levels show lower mercury concentrations. At Southern Indian Lake this is emphatically the case; lake whitefish are clearly a safer choice for eating. At Lake Athabasca, small goldeye actually showed higher concentrations than small pike. This suggests there is greater variability in rates of bioaccumulation than might be expected, and that it is shaped by complex local factors. This could warrant further study and evinces the need for more consistent data collection, which was undermined by the closure of the mercury lab in 2006 and funding cuts to Fisheries and Oceans Canada in the early 2010s. With interest rising in building sustainable communities and small-scale indigenous fisheries, robust contaminant monitoring should be a national priority.

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